



**US Army Corps
Of Engineers®**
Charleston District

CHARLESTON HARBOR MORPHOLOGY EVALUATIONS

CHARLESTON HARBOR DEEPENING PROJECT (POST 45)



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Prepared by

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CHARLESTON HARBOR MORPHOLOGY EVALUATIONS

1. INTRODUCTION

Charleston Harbor is a natural tidal estuary formed by the confluence of the Cooper, Ashley, and Wando Rivers. Charleston Harbor is bordered by the Atlantic Ocean to the east, the city of Charleston to the west, Mount Pleasant and Sullivan's Island to the north and James Island and Morris Island to the south (figure 1). The study area is located in Berkeley and Charleston Counties, South Carolina (USACE, 2010). The Charleston Harbor Federal Navigation Channel is divided into three primary reaches: the entrance channel, lower harbor, and upper harbor reaches. The entrance channel begins at the 47-foot contour line in the Atlantic Ocean and extends northwest 17 miles to the harbor entrance between Fort Moultrie and Fort Sumter. The lower harbor includes the Anchorage Basin, Rebellion Reach, Bennis Reach, Horse Reach, Hog Island Reach, Drum Island Reach, Myers Bend, Wando River Lower Reach and Wando River Upper Reach (ANAMAR, 2013).

The existing Charleston Harbor federal navigation project currently provides limited 2-way traffic and consists of channels, turning basins, an anchorage basin, contraction dikes, jetties, and dredged material disposal areas. The channels have been enlarged through the past 160 years, and the authorized depth supporting the major terminals is 45 feet MLLW. Construction of the existing project was initiated in 1998 and completed in 2004. All of the changes authorized in 1996 have been completed with the exception of the Daniel Island Turning Basin as the terminal it would have serviced was relocated to the former Naval Base (USACE, 2015).

The 2015 feasibility study (USACE, 2015) presents the results of investigations and analyses conducted to evaluate modifications to the existing Federal navigation system (figure 2) to improve its ability to efficiently serve the current and future vessel fleet and process the forecasted cargo volumes. It presents a survey of existing and future conditions and evaluates cost savings that would be generated by the constructing and maintaining the improvements over a 50-year study period. The selected improvement would deepen the inner harbor channels leading to the Wando Welch container facility and the new Navy Base Terminal from the existing -45 feet MLLW to -52 feet MLLW, and the channel from the new Navy Base Terminal to the North Charleston container facility from -45 feet MLLW to -48 feet MLLW. The entrance channel would be deepened from -47 feet MLLW to -54 feet MLLW. There is general agreement related to the project's overall lack of adverse impacts to waves, currents and erosion in Charleston Harbor area. However, it is difficult to accurately predict effects at specific locations with a high degree of confidence. Based on this uncertainty and the presence of several significant natural and historic resource, the USACE agreed to monitor for unanticipated adverse impacts to significant natural and historical resources in Charleston Harbor. Monitoring could detect unanticipated adverse impacts but the likelihood is considered low.

The primary objective of the proposed study is to evaluate the potential impacts of the deepening project on hydrodynamics and coastal morphology within the Charleston Harbor coastal area.

The Coastal Modeling System (CMS) is an integrated suite of numerical models for simulating water-surface elevation, current, waves, sediment transport, and morphology change in coastal and inlet applications. CMS-Wave model (Lin et al., 2008) was used to calculate wave transformation. The CMS-Flow model (Buttolph et al., 2006) estimates water surface elevations, two components of the current and sediment transport. Sediment transport and morphology change can be computed as a user-specified option. The models calculate time-dependent water elevation, current speed and direction, erosion and accretion and sediment transport flux.

CMS flow and wave models used in this study were developed and applied previously for the Charleston Harbor numerical modeling study (USACE, 2013), to assess the flow patterns, sediment transport pathways and morphology change in the jetties and Morris Island vicinity. These foundation models were modified to accurately estimate changes in the nearshore environment caused by the deepening project.

Field data collected during a previous Charleston Harbor numerical modeling study (USACE, 2013) which included nearshore bathymetry, current and wave measurements, were used in the present modeling work. Astronomical tide, measured river flow and wave data were used to force the CMS-Flow and CMS-Wave models. CMS modeled current and wave data were compared to measured data. Hydrodynamics and morphology changes in the Charleston Harbor area were investigated during representative long and short extreme weather periods.

Three scenarios were used to investigate how deepening the Charleston Harbor Channel would affect hydrodynamics and morphology in the vicinity of the Charleston Harbor. Base, Future With Project (FWP) and Future Without Project (FWOP) conditions were investigated in this study. The base conditions are an estimate of possible conditions that may exist at the approximate time that the project is completed. FWP and FWOP conditions represent future states beginning in project year one and extending over a 50-year period of analysis. For the purposes of this study, the years 2022 through 2071 were examined.

Without-project and with-project conditions were evaluated for effects on the hydrodynamics and morphology change. Also, potential influence of sea level rise on water levels, current and morphology change in the vicinity of the Charleston Harbor and shorelines was examined.



Figure 1- Charleston Harbor Federal Navigation Channel Reaches (USACE, 2010)

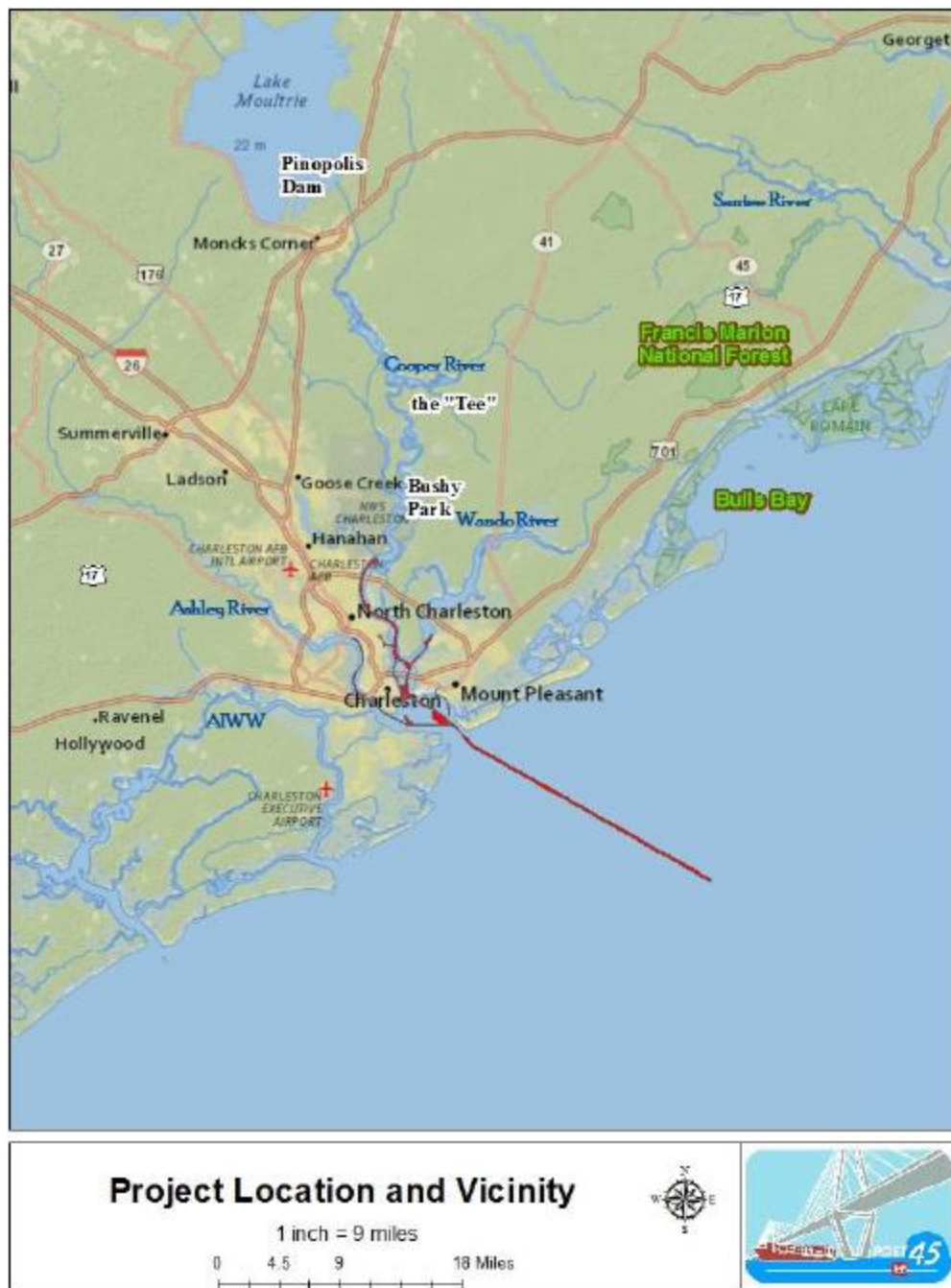


Figure 2- Charleston Harbor Federal Navigation system and vicinity (USACE, 2015)

2. HISTORIC AND EXISTING CONDITIONS

2.1 Historic Background

The earliest sketch of Charleston Harbor Inlet (1779) by the British Navy (figure 3) indicates the ebb-tidal delta was strongly asymmetric with the majority of the delta south of Charleston Harbor. At this time the main-ebb channel was diverted southward along Morris Island and turned seaward at Lighthouse Inlet, which is located between Morris Island and Coffin Island (now Folly Island). Ebb-tidal shoals appear to have extended from Sullivans Island to Lighthouse Inlet (Hansen and Knowels, 1988).

(Andes et al., 1990) stated that the northwest side of Charleston Harbor entrance is formed by Suvillian's Island. Accretion in the vicinity of Fort Moultrie has been adequately measured by shoreline mapping technique. Southwest of Charleston Harbor is Cumming Point, on Morris Island. From 1857/58 to 1900, Cummings Point retreated alongshore approximately 600 m. This coincided with landward erosion of the entire northern portion of Morris Island; prior to jetty completion in 1895. From 1900 to 1955, Cummings Point grew northward into the harbor approximately 600 m. From 1955 to 1983, there was no net change. Net change from 1857/58 to 1983 was a slight increase in length of approximately 60 m.

USACE (scanned document) stated that post Jetty construction analyses (1900/1910-1983) shows that Morris Island retreated significantly with most of the retreat occurring from the middle to the south part of the island. This resulted in an overall shift in the long axis of the island to the west, rotating about the north end. The north end of Morris Island has advanced and retreated several times during the past 85 years. The shoreline on north Folly Island also eroded. The Isle of Palms accreted uniformly while the majority of accretion on Sullivan's Island occurred south of the north jetty.



Figure 3- 1779 drawing of Charleston Harbor Inlet (Hansen and Knowels, 1988)

(Hansen and Knowels, 1988) shows that Jetty construction has confined tidal flow between the jetties, resulting in "tidal flow abandonment" of natural ebb and marginal flood channels (figure 4). Because ebb-tidal deltas form due to a balance of tidal and wave forces, confinement of flow within the new channels caused wave dominance of adjacent relict ebb-tidal delta areas. Landward bar migration occurred due to wave induced sediment transport. At Charleston Harbor, greater tidal prism, water depth, and ebb-tidal delta size, in combination with a significant southerly alongshore sediment transport rate, has resulted in different response characteristics. Although landward swash platform and terminal lobe migration occurred, no welding of material on downdrift beaches has occurred. Greater water depths present across the Charleston Harbor Inlet ebb-delta may have decreased the significance of landward wave-induced sediment transport. This decreased response, in terms of speed and magnitude, could mean that migration of the old swash platforms is still occurring and will continue.

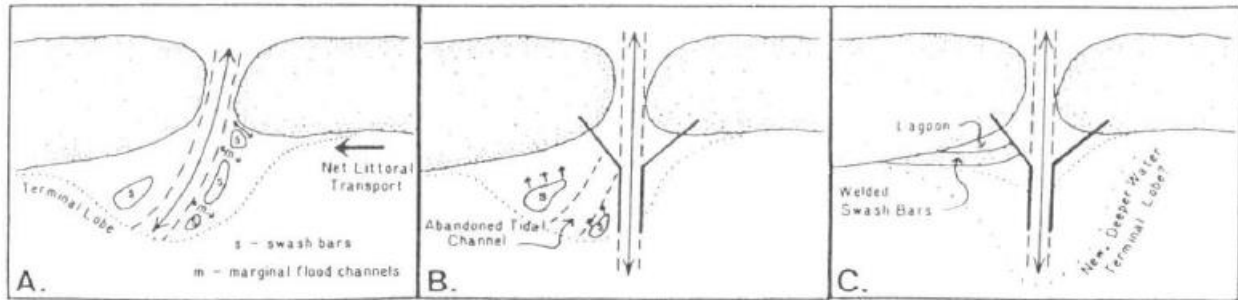


Figure 4- Model for response of ebb-tidal delta to jetty construction. A) pre- construction configuration; B) forced "tidal abandonment" of main ebb channel, ebb shoals, and marginal flood channels due to jetty construction causes wave dominance of ebb-tidal delta areas, resulting in landward sediment transport; C) beach ridge welding and formation of lagoon on downdrift side and possible new, deep water ebb-tidal delta formation (Hansen and Knowels, 1988).

(Stapor and May, 1987) stated that Charleston Harbor Entrance, a tide-dominant (ebb-directed) inlet has a lunate ebb-tidal delta pierced by twin jetties constructed between 1884 and 1896. Computer simulation, using pre- and post-jetty bathymetries, indicates that littoral drift is presently and was historically inlet directed, south along islands to the north and north along islands to the south. Sediment budgets determined from map differencing of pre- and post-jetty bathymetries (1865-1964) indicate that net erosion of the ebb-tidal delta has systematically decreased since jetty construction as has also net erosion of Morris Island, the adjacent barrier island to the south. Computer simulation of littoral drift, sediment budgets determined by map differencing, tidal-current transport, and nature of the unconsolidated sediments covering the channel's floor-indicate that jetty construction at Charleston Harbor Entrance has not adversely affected the natural system. It is not responsible for coastal erosion on the barrier islands to the south nor has it accelerated the offshore movement of sand from the Charleston Entrance ebb-tidal delta. Rather, jetty construction has allowed Morris Island to receive sand from the offshore ebb-tidal delta at a rate sufficient to balance its natural erosion, which should systematically decrease as the nearshore geometry changes because of the landward migration of the ebb-tidal delta.

USACE (2015) conducted shoreline change analysis to determine recent historic changes in the shoreline features within Charleston Harbor, SC where channel modifications of deepening and widening have occurred. Methodology was a GIS analysis using aerial imagery from 1994 to 2011 in order to detect shoreline changes within the harbor. The earliest readily available spatial data was 1994 and represents an after deepening condition of the 40-foot channel deepening project. The dataset from 1999 represents a condition just prior to the 45-foot deepening project and the 2006 data represents the condition after the 45-foot deepening. The 2011 imagery represents approximately 6 years after the completion of 45-foot project. The data used in the 2015 feasibility study was used to assess the shoreline change along Sullivan's and Morris Islands.

Figure 5 shows the 1994, 1999, 2006 and 2011 images of Sullivan's Island. The images show landward swash platform migration and welding of material on the eastern portion of Sullivan's Island. The 2011 image shows the delineated 1994 and 2011 shorelines which addresses major accretion along the Island's shoreline.

Figure 6 shows the 1994, 1999, 2006 and 2011 images of Morris Island. The images show that the shorelines along Morris Island are slightly eroding with accretion at Cummings Pt and Lighthouse inlet.



Figure 5 - Aerial photographs of Sullivan's Island

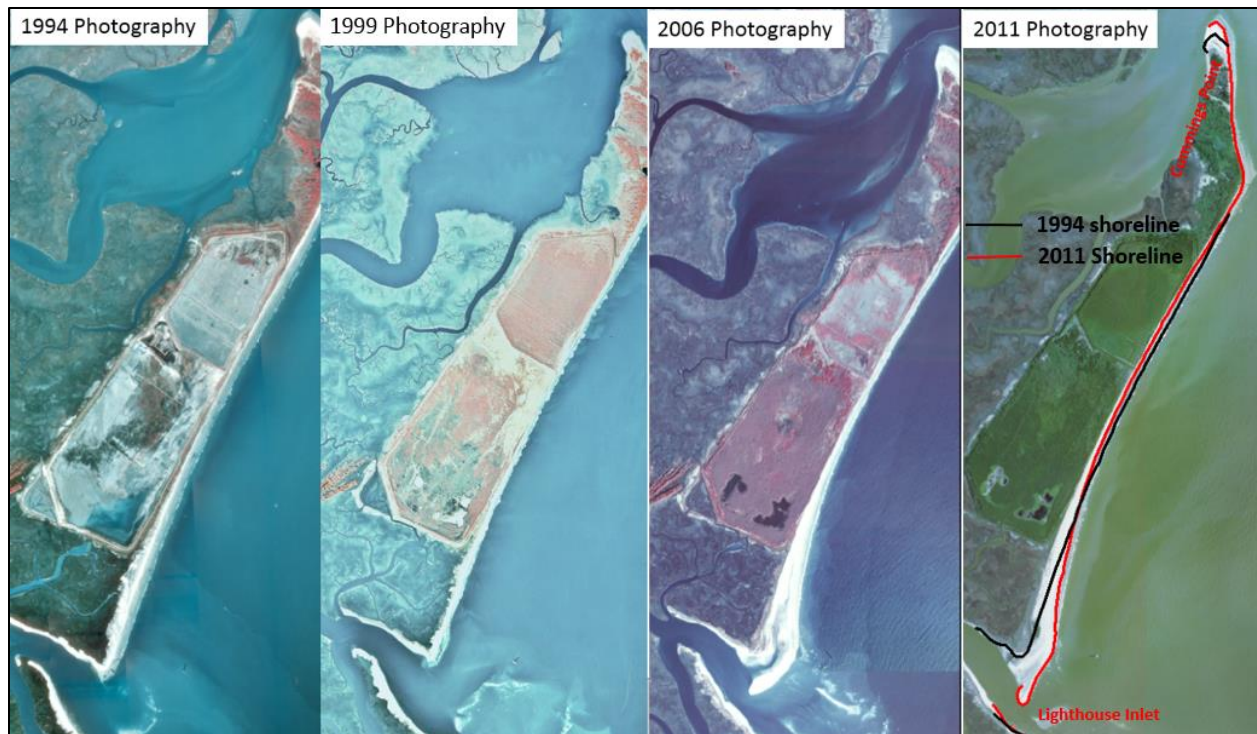


Figure 6 - Aerial photographs of Morris Island

2.2 Existing Conditions

The existing coastal processes in the study area are established and used as models input to determine the potential impacts of the deepening project within the vicinity of Charleston Harbor. Representative existing tides, currents and circulations, Sea Level Rise (SLR), river flow, wave data, wind data and bathymetric surveys are identified from literature and available databases.

2.2.1 Tides

USACE (2015) stated that the tidal range throughout the interior channels is relatively uniform. The astronomically-generated high and low tides within the Federal channel range from about 5 to 6 feet above MLLW over the year. Figure 7 shows the location of the National Oceanic and Atmospheric Administration (NOAA) Charleston, SC station (8665530). Table 1 shows the tide range from the NOAA Benchmark Sheet for 8665530, published 4/29/2003, based on tidal epoch 1983-2001 (USACE, 2015).

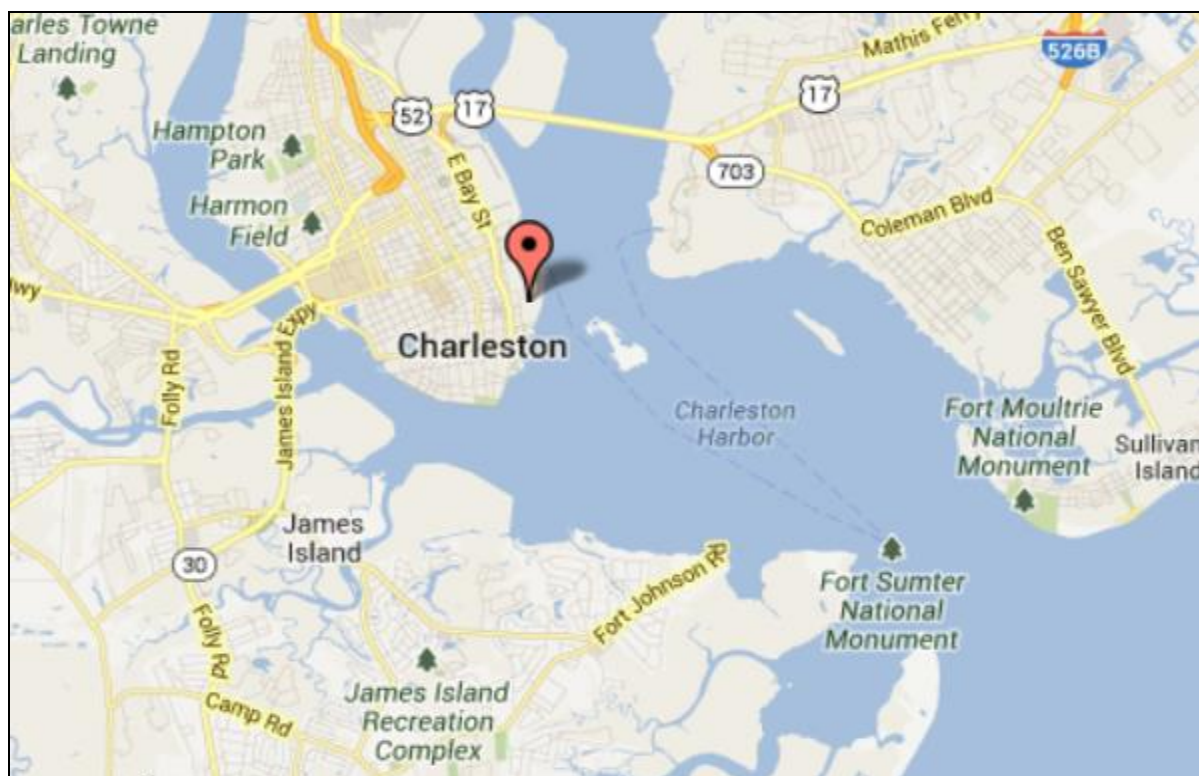


Figure 7– Location of NOAA Charleston, SC station (8665530)

Table 1- Tide Range (USACE, 2015)

Elevations of tidal datums referred to Mean Lower Low Water (MLLW),			
		meters	feet
HIGHEST OBSERVED WATER LEVEL (09/21/1989)		3.817	12.52
MEAN HIGHER HIGH WATER	MHHW	1.757	5.76
MEAN HIGH WATER	MHW	1.648	5.41
North American Vertical Datum	NAVD88	0.957	3.14
MEAN SEA LEVEL	MSL	0.891	2.92
MEAN TIDE LEVEL	MTL	0.853	2.80
MEAN LOW WATER	MLW	0.057	0.19
MEAN LOWER LOW WATER	MLLW	0	0.00
LOWEST OBSERVED WATER LEVEL (03/13/1993)		-1.245	-4.08
Based on North American Vertical Datum (NAVD88)			

2.2.2 Currents

USACE (2015) stated that ebb (falling tide) currents near the entrance to Charleston Harbor are generally about 1 knot (about 1.69 feet/second) while ebb currents near Fort Sumter and Drum Island may reach 4 knots (6.75 feet/second).

The Environmental Protection Agency (EPA) collected current and wave data at the locations shown in figure 8 during 2012-2013 as part of a study to designate a new Charleston Harbor Ocean Dredged Material Disposal Site (ODMDS). This task involves multiple deployment and retrievals of Acoustic Doppler Current Profilers (ADCP) to measure currents and waves within the proposed modified ODMDS study area and around the Charleston Harbor Entrance Channel (EPA, 2014). A current rose for depth average currents for RSM-N and RSM-S stations are shown in figures 9 and 10 respectively. The RSM-N station has a predominately west-southwest flow and the RSM-S station has a north-northwest and east-southeast flow. The Offshore station does not have a dominant flow direction although the strongest currents flow northeast and southwest as shown in figure 11 which depicts the current rose at the Offshore station (EPA, 2014).

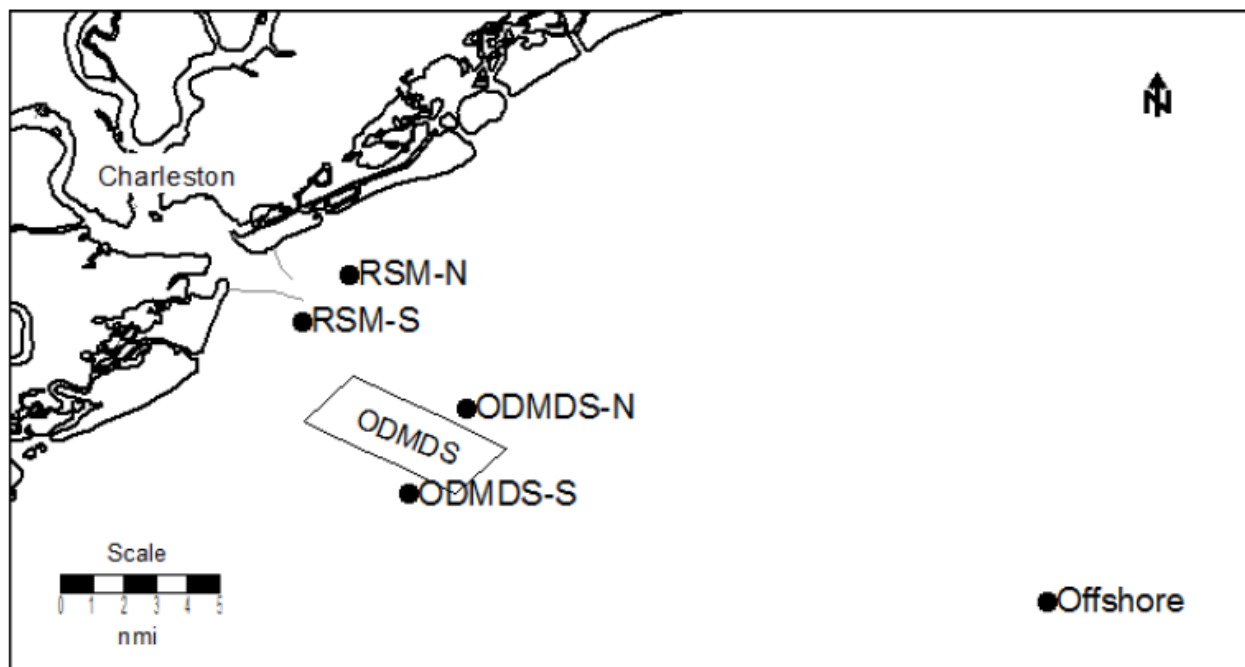


Figure 8- Station location map (EPA, 2014)

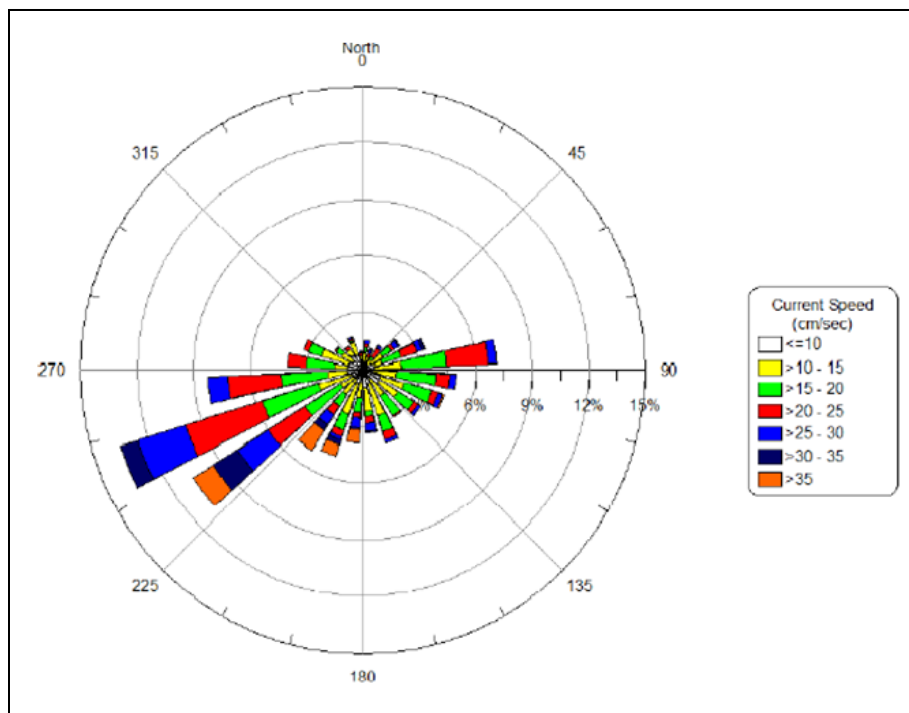


Figure 9- Current rose at the RSM-N station (EPA, 2014)

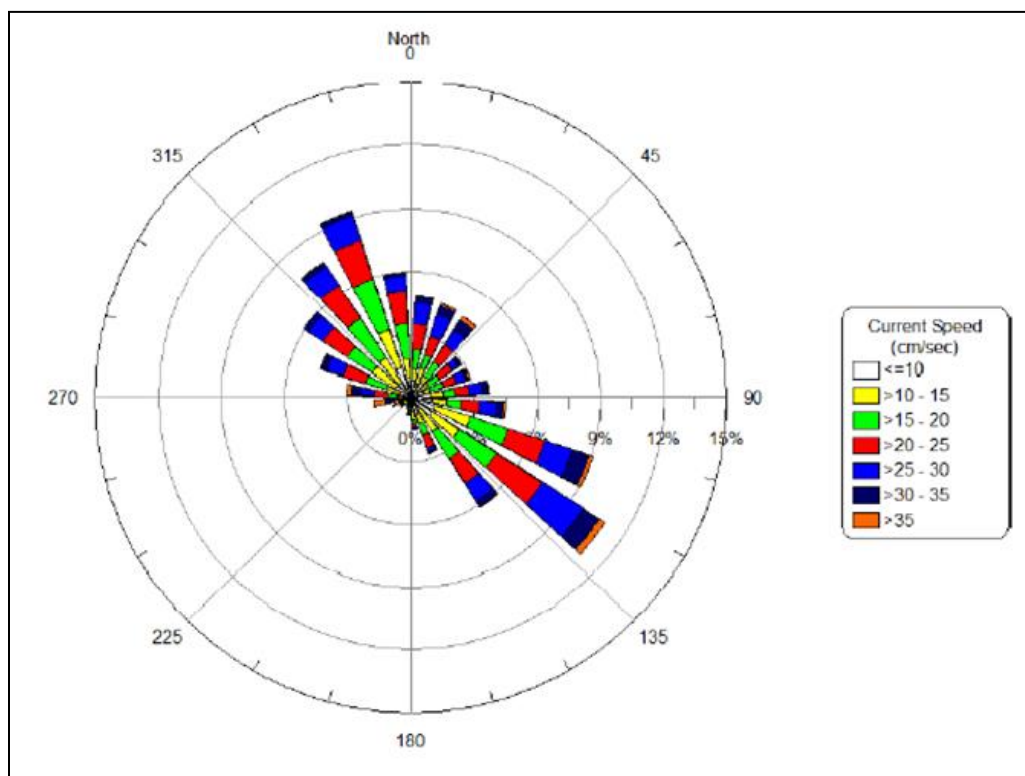


Figure 10- Current rose at the RSM-S station (EPA, 2014)

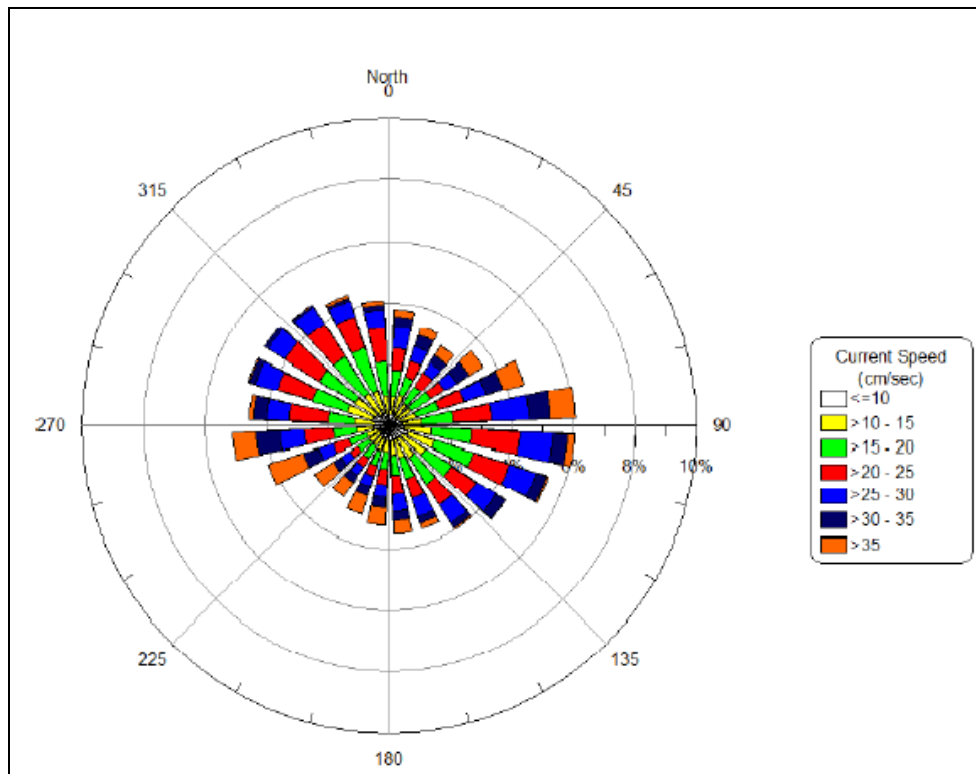


Figure 11- Current rose at the Offshore station (EPA, 2014)

2.2.3 Sea Level Rise

USACE (2015) stated that recent climate research by the Intergovernmental Panel on Climate Change (IPCC) predicts continued or accelerated global warming for the 21st Century and possibly beyond, which will cause a continued or accelerated rise in global mean sea-level. USACE Engineering Regulation ER 1110-2-8162 “Incorporating Sea Level Change into Civil Works Programs” was developed with the assistance of coastal scientists from the NOAA National Ocean Service and the US Geological Survey (USGS). Planning studies and engineering designs are to evaluate the entire range of possible future rates of sea-level change (SLC), represented by three scenarios of “low”, “intermediate” and “high” sea-level change (figure 12). The use of sea level change scenarios as opposed to individual scenario probabilities underscores the uncertainty in how local relative sea levels will actually play out into the future. At any location, changes in local relative sea level (LRSL) reflect the integrated effects of global mean sea level (GMSL) change plus local or regional changes of geologic, oceanographic, or atmospheric origin. Using the USACE Institute of Water Resources (IWR) Sea Level Change calculator spreadsheet the trend at Charleston is estimated to be 2.94 mm/yr based on CO-OPS gage 8665530.

2012 tidal data is used for the analysis of existing conditions because the numerical models will be forced with measured data collected during 2012-2013. Estimating construction completion of 2021, and a 50 year project life, starting with 2012 (thus estimate the increase in 59 years) – the rates of change relative to Charleston Harbor are as follows: “low” rate of change is 0.57 feet, the “intermediate” is 1.08 feet and the “high” is 2.74 feet (Table 2).

Table 2- Sea Level Change Rates (USACE, 2015)

Sea Level Change (feet)			
Year	Low	Int	High
2012	0.00	0.00	0.00
2015	0.03	0.04	0.08
2020	0.08	0.11	0.22
2025	0.13	0.19	0.38
2030	0.17	0.27	0.56
2035	0.22	0.35	0.76
2040	0.27	0.44	0.98
2045	0.32	0.53	1.21
2050	0.37	0.63	1.47
2055	0.41	0.73	1.74
2060	0.46	0.84	2.03
2065	0.51	0.95	2.34
2070	0.56	1.06	2.67
2075	0.61	1.18	3.01

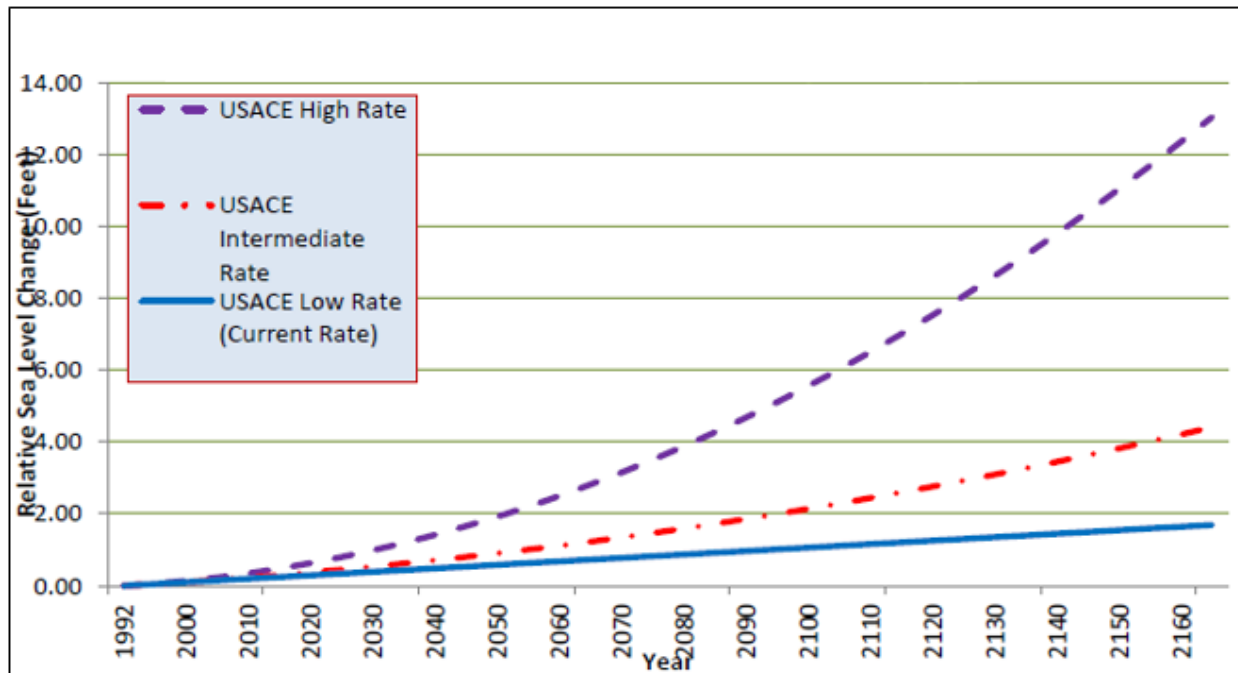


Figure 12- Relative Sea Level Changes for Charleston Harbor (USACE, 2015)

2.2.4 River Flow

Figure 13 shows the location of the USGS gauges of the major three rivers discharging into Charleston Harbor. Parchure and Teeter (2003) stated that a large amount of water from the Santee River was diverted to the Cooper River in 1942 as part of a power generation project.

This increased the average annual freshwater discharge into Charleston Harbor from 23 m³/sec to between 57 and 792 m³/sec depending on the electrical demand. Representative flow for Ashly, Cooper and Wando rivers are 400 ft³/sec, 9800 ft³/sec and 2200 ft³/sec respectively.



Figure 13- Location of the USGS gauges

2.2.5 Wave Climate

Figure 14 shows wave height rose for the entire deployment period at the Offshore station (EPA, 2014). Waves are predominately out of the east-southeast and few exceed 2.5 meters at the Offshore station.

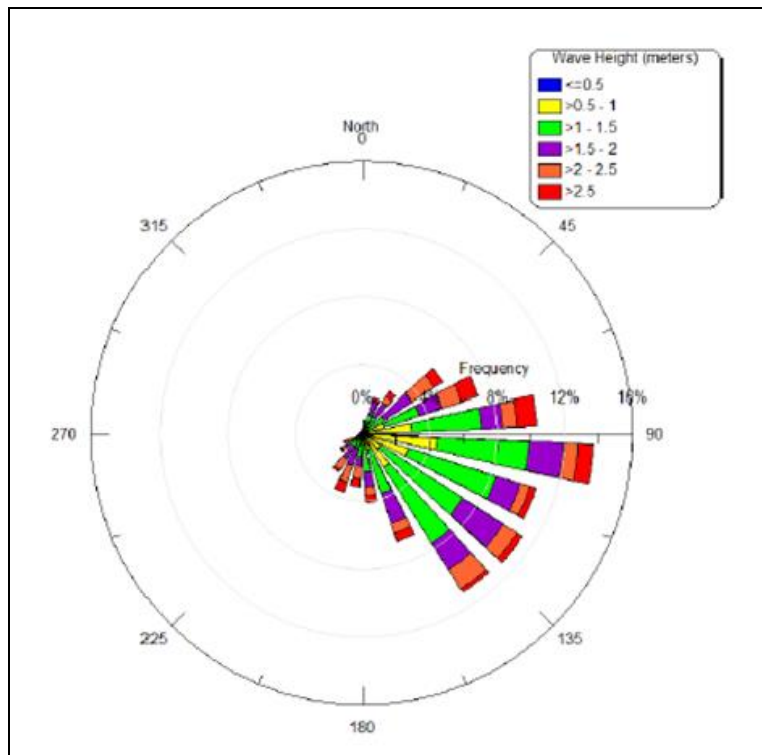


Figure 14- Wave height rose at the Offshore station (EPA, 2014)

2.2.6 Wind

Measured wind data in the vicinity of Charleston Harbor area is available at the following three stations (figure 15):

- NOAA Charleston station
- National Data Buoy Center (NDBC) 41029
- NDBC Folly Island station

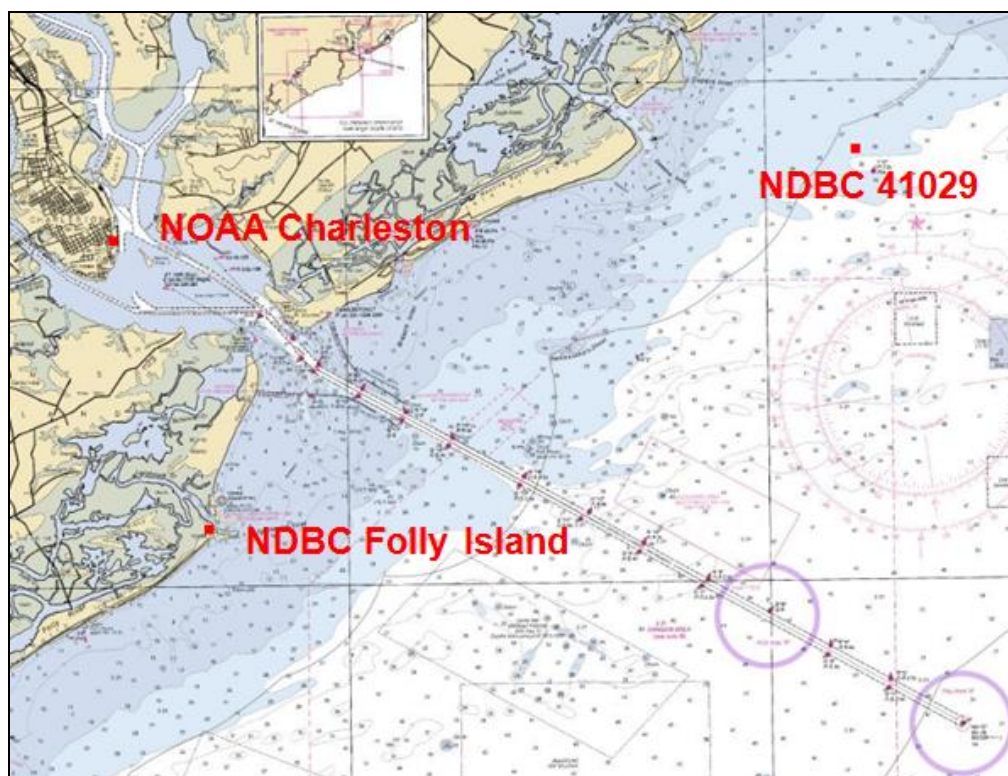


Figure 15- Location of wind stations

Figure 16 presents a wind rose generated using the hourly averaged data (wind speed and direction) recorded between January 2010 and December 2011 at the NOAA data collection station in Charleston Harbor. As illustrated, winds are predominantly from the southwest, but the strongest winds (fastest 10%) are predominantly from the north-northeast (USACE, 2015).

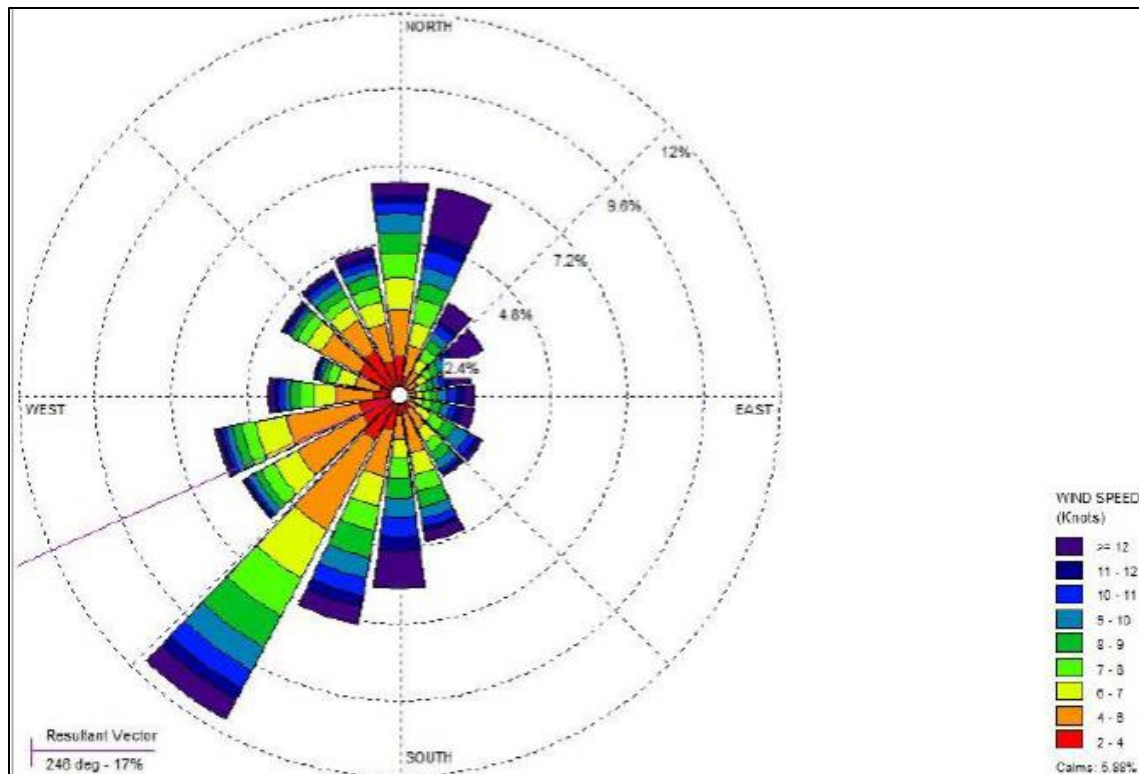


Figure 16- Wind rose for Charleston Harbor depicting wind direction and speed frequency (USACE, 2015)

2.2.7 Bathymetry

The bathymetry was obtained from previous report (USACE, 2013) and was collected by:

- The Center for Marine and Wetland Studies (CMWS) at Coastal Carolina University (CUU) conducted hydrographic surveys for major tidal inlet features of Charleston Harbor from August 2009-August 2010.
- Charleston District
- NOAA digitized charts

2.2.8 Sediments

Physical analysis results from the U.S. Army Corps of Engineers Charleston District (SAC) 2010 cores in the Lower Harbor and the Entrance Channel was used to extract the median sediment grain size (D50) values from the core logs. Also, the usSEABED database was used to augment the available SAC data and obtain better coverage for the study area. usSEABED provides a digital, integrated database of existing physical data and information from the seafloor, including textural, statistical, geochemical, geophysical, and compositional information. D50 values obtained from SAC and the usSEABED database of the U.S. Geological Survey and the University of Colorado (<http://walrus.wr.usgs.gov/usseabed/>) were examined to accurately

represent the spatial distribution (figure 17) of sediment within the model domain (USACE 2013).

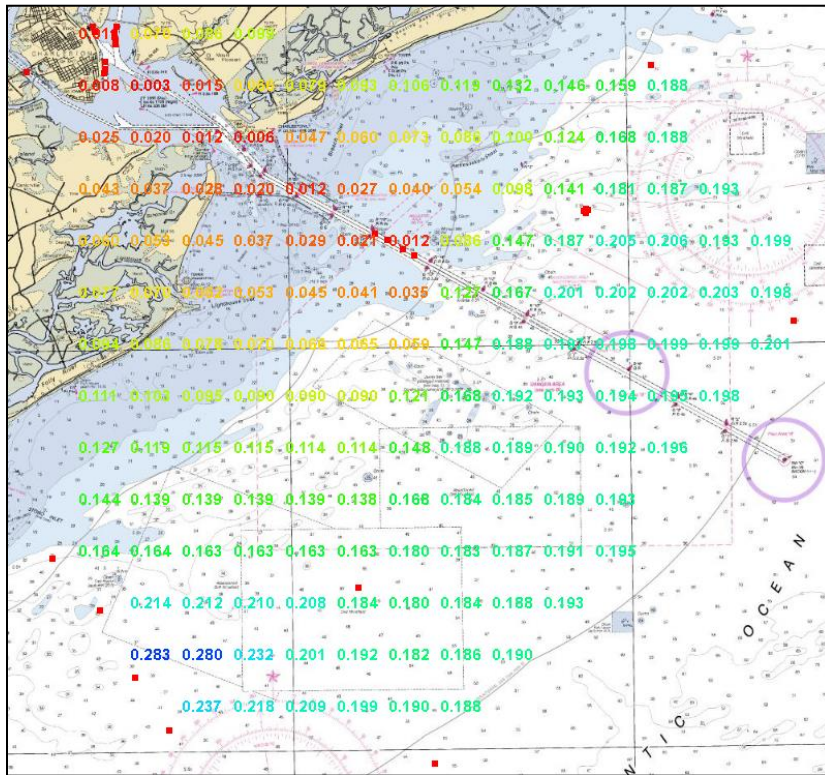


Figure 17- Distribution of D50 (mm) in the Charleston area (red points show location of SAC and usSEABED samples)

3. SIMULATION SCENARIOS

USACE (2015) proposed to extend and deepen the Entrance Channel in combination with deepening and widening the inner harbor channels that primarily serve containerships. The proposed navigation improvements are described in more detail in the bullets and text that follow:

- Deepen the existing Entrance Channel from a project depth of -47 feet to -54 feet MLLW over the existing 800-foot bottom width, while reducing the existing stepped 1,000-foot width to 944 feet from an existing depth of -42 feet to a depth of -49 feet MLLW. The proposed deepening of the Entrance Channel also includes 1 to 2 feet of required overdepth dredging for Entrance Channel Segment 2 and advanced maintenance for Entrance Channel Segment 1 and up to 2 feet of allowable overdepth dredging.

- Extend the Entrance Channel approximately three miles seaward to about the -57 foot MLLW contour.
- Deepen the inner harbor from an existing project depth of -45 feet to -52 feet MLLW to the Wando Welch Terminal on the Wando River and the new SCSPA Navy Base Terminal on the Cooper River, and from -45 feet to -48 feet MLLW for the reaches above that facility to the North Charleston Terminal (over varying expanded bottom widths ranging from 400 to 1,800 feet). The proposed deepening of the inner harbor also includes overdepth dredging and advance maintenance dredging.
- Enlarge the existing turning basins to an 1,800-foot diameter at the Wando Welch and new Navy Base Terminals to accommodate Post-Panamax Generation 2 and 3 containerships.
- Enlarge the North Charleston Terminal turning basin to a 1,650-foot diameter to accommodate Post-Panamax Generation II and Generation III containerships.

Figure 18 shows the proposed extension and deepening of the Entrance Channel in combination with deepening and widening the inner harbor channels. Three scenarios are used to investigate how deepening the Charleston Harbor Channel would affect hydrodynamics and morphology in the vicinity of the Charleston Harbor as stated in Table 3. The base conditions in this study are an estimate of possible conditions that may exist at the approximate time that the project is completed. Future With Project and Future Without Project conditions represent future states beginning in project year one and extending over a 50-year period of analysis. For the purposes of this study, the years 2022 through 2071 were examined.

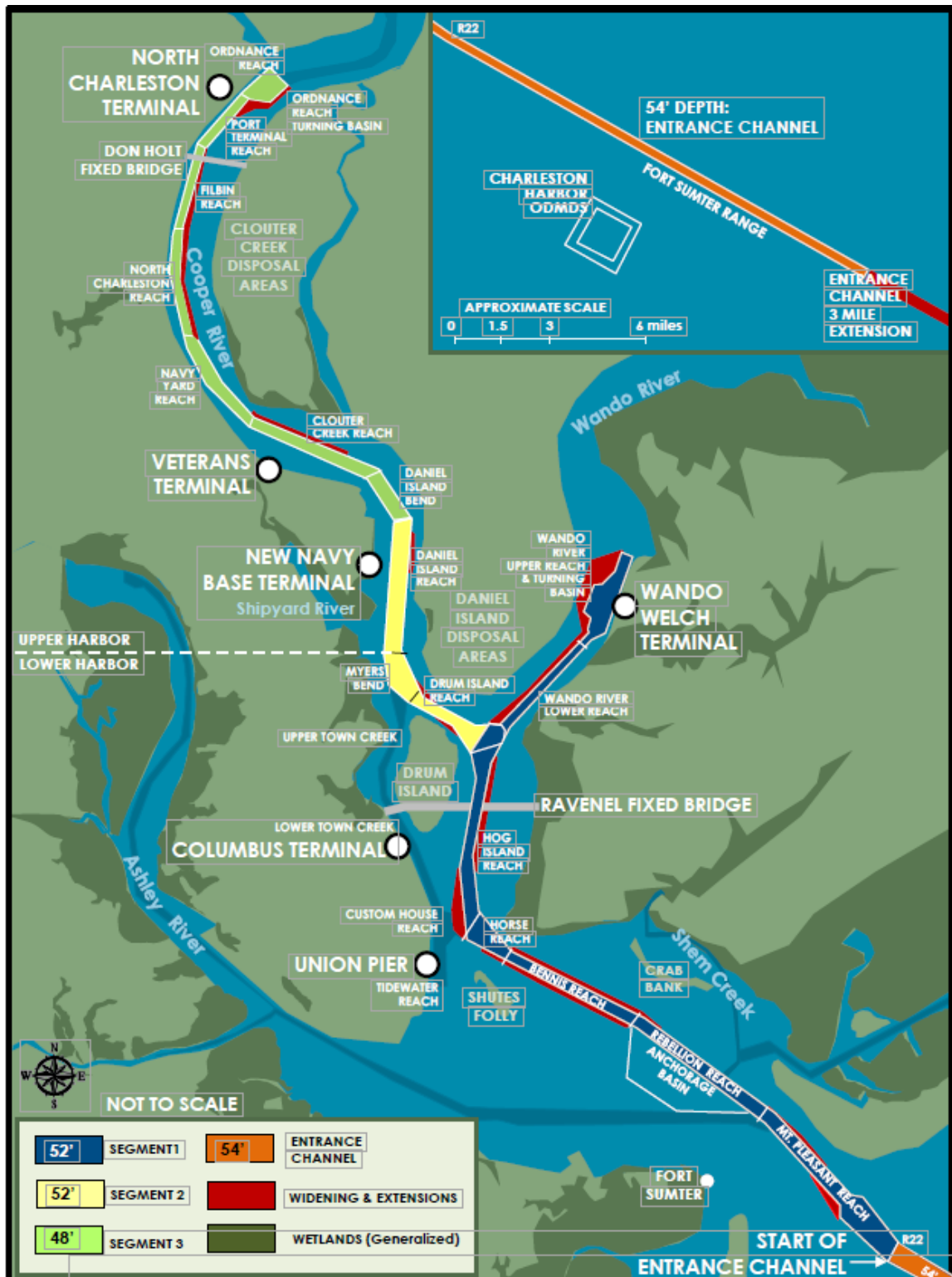


Figure 18 – Charleston Harbor recommended deepening (USACE, 20150)

Table 3- Simulation Scenarios

Scenario	Channel Depth (ft)	Project Year
1	45 (without project)	Base (2022)
2	45 (without project)	Future (2071)
3	52 (with project)	

4. HYDRODYNAMIC AND WAVE MODELING

The CMS is an integrated suite of numerical models for simulating water-surface elevation, current, waves, sediment transport, and morphology change in coastal and inlet applications. CMS-Wave model calculates wave transformation and CMS-Flow model estimates water surface elevations, two components of the current and sediment transport. Sediment transport and morphology change can be computed as a user-specified option. The models calculate time-dependent water elevation, current speed and direction, erosion and accretion and sediment transport flux.

CMS flow and wave models that were developed and applied previously for the Charleston Harbor numerical modeling study (USACE, 2013) were used in this study. Details of the models calibration and verification efforts can be obtained from USACE (2013). These foundation models were modified and used to assess coastal morphology in the area. The present modeling effort adopted the same models with the following main modifications:

- Increase the grids resolution in the vicinity of the southern portion of Morris Island.
- Increase the length of the grid offshore to include the proposed three miles extension of the Entrance Channel.
- Increase the resolution within the existing and proposed extension of the Entrance Channel area.
- Increase the marsh area coverage along Ashley, Cooper, and Wando Rivers.
- Increase the roughness in the marsh areas.

Figure 19 shows the boundaries of the CMS-Flow and CMS-Wave grids.

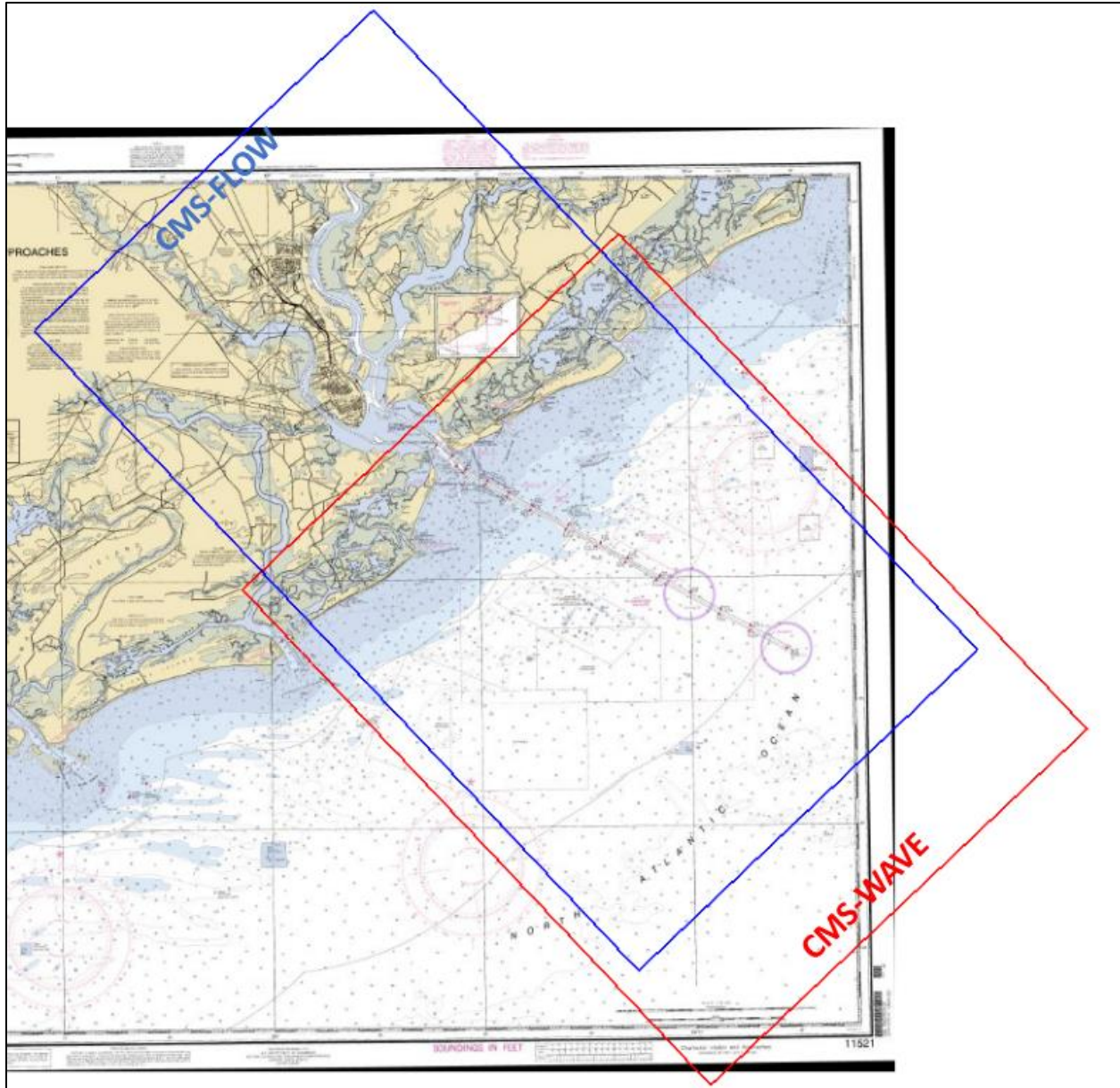


Figure 19- CMS-Flow and CMS-Wave grids domain

4.1 Models Setup

A variable-resolution grid system was used to discretize the nearshore and offshore regions of the CMS-Flow grid. High resolution was implemented in the nearshore area to adequately resolve details of the marshes, jetties and nearshore features. Small grid cells in the nearshore zone are required to capture wave breaking and breaking-induced sediment transport. The model geometry is defined by the shorelines of the study area obtained from bathymetry. Aerial photographs and Nautical Charts were overlaid on the grid to define structures and marshes boundaries. The finest resolution of about 7 m was adopted to resolve the crest of the jetties and

the maximum cells sizes in the offshore area were set to 400 m. CMS models require accurate bathymetry data to construct computational grid over which circulation patterns are resolved and waves propagate and transform. Bathymetry data used in USACE (2013) were adopted for this study. Channel survey data measured during June 25 of 2013 was used to update the Entrance Channel bathymetry. The survey data was referenced to the horizontal State Plane Coordinate System (NAD83) in meters and to the vertical Mean Tidal Level (MTL) datum which represents the vertical datum of the model. Charleston, SC station (8665530) was used to reference the data to MTL. A merged bathymetric scatter set was interpolated to the CMS-Flow Cartesian grid. Some areas of the grid, away from the inlet area, were fairly represented due to data availability and grid resolution. Figure 20 shows the variable resolution CMS-Flow grid. The telescoping, variable-resolution grid, system is not available to develop the wave grid. Therefore, nonuniform Cartesian grid with local refinement within the shorelines, jetties and channel areas was adopted as shown in figure 21. The grid cells defining the jetties were set as rubble mound breakwater structure.

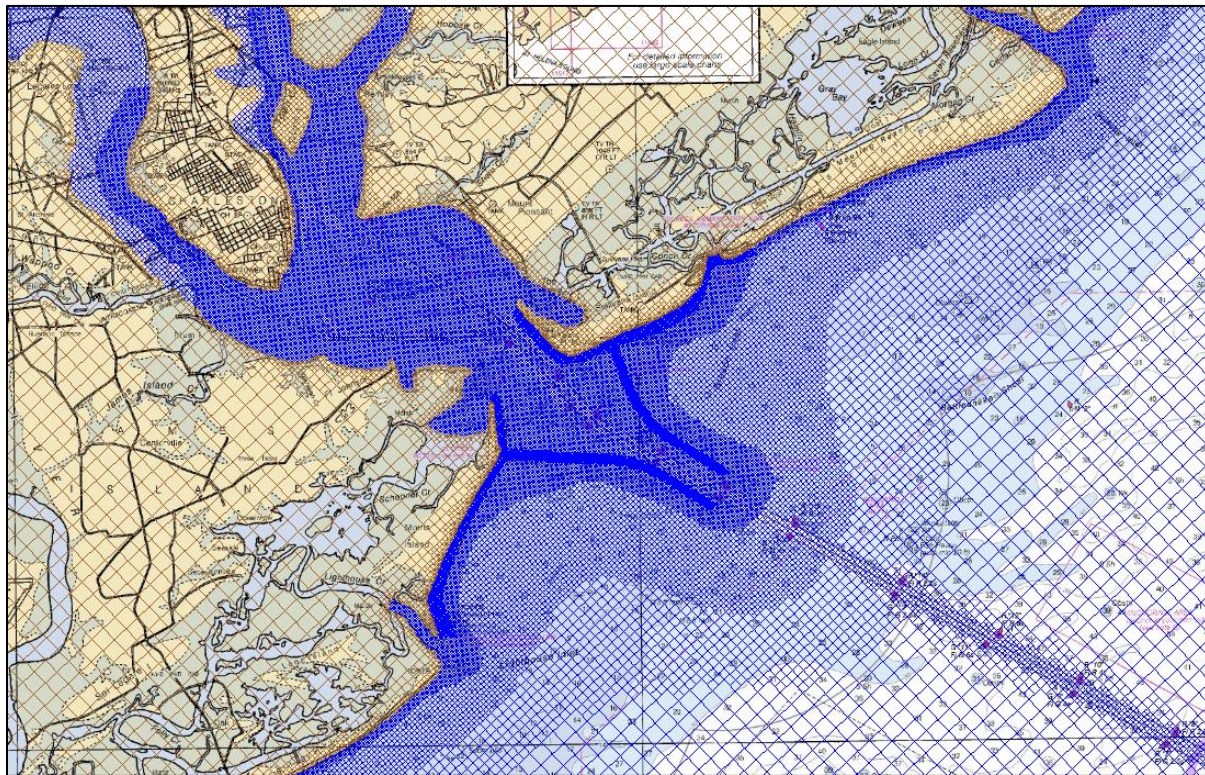


Figure 20- Variable resolution CMS-Flow grid

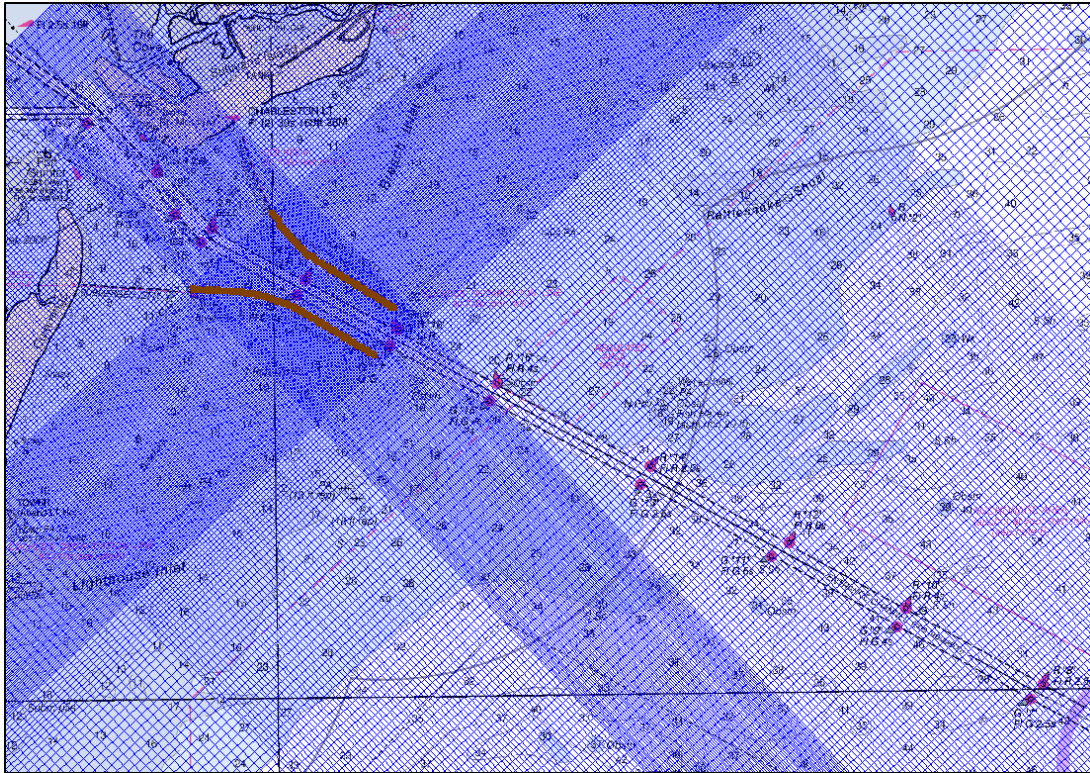


Figure 21- Nonuniform CMS-Wave grid

The CMS-Flow model is forced at the ocean boundary with time series of water level extracted for each cell along the ocean cellstring. The water levels were extracted from the U. S. East Coast Tidal Database (EC2001) calculated with the Finite Element model ADCIRC (Mukai et al., 2002). Surface-water Modeling System (SMS) 11.0 does not extract the tidal constituents for CMS. Therefore, CMS-Flow Advanced Cards were used to define the tidal constituents forcing. Also, the model is forced with hourly wind speed and direction and with constant monthly average flow rate at Ashley, Cooper and Wando rivers.

The CMS-Wave model is forced with wave spectra every three hours at the offshore grid boundary and with wind data.

All of the CMS-Flow model parameters, settings, and output options are controlled from the CMS-Flow Model Control window. The window also has a section for Advanced Cards in which new features which have not been incorporated into the SMS interface yet or more advanced model features for more experienced users.

The inline version of CMS-Flow, which includes CMS-Flow and CMS-Wave in one code, is adopted in this study because of its capability to implement the tidal constituent forcing at the ocean boundary for telescoping CMS grids. The surface roller model is also included. As a wave transitions from nonbreaking to fully breaking, part of the energy is converted into momentum which goes into the aerated region of water known as the surface roller. Under the assumption that the surface roller moves in the mean wave direction, the evolution and dissipation of the surface roller energy is calculated by an energy balance equation. It is recommended to always turn on the

surface roller model. The results, have been shown to significantly improve when simulating nearshore currents and water levels (Sanchez et al. 2011).

4.2 Hydrodynamic and Wave Models Calibration

The CMS models were recalibrated because the original grids were modified. The models were calibrated during the same calibrations period (November, 2012) used in USACE (2013). The CMS-Flow model was forced with:

- Time series of water level extracted from the EC2001 tidal database
- Hourly wind speed and direction at the National Data Buoy Center (NDBC) 41029
- Constant monthly average flow rate of 11.33, 277.5 and 62.3 m³/sec at Ashley, Cooper and Wando rivers respectively

EPA Region 4 conducted a one year study of the currents and waves in the vicinity of a new ODMDS in support of site designation (McArthur, 2012). Depth and roughness of the marsh areas was adjusted to obtain better agreement between modeled water level and current velocity data and measured data collected at RSM-S ADCP (figure 8).. Figures 22 and 23 show the comparison between measured and modeled water level and current magnitude at RSM-S ADCP during November 10-30, 2012.

The Index of Agreement (USACE, 2015):

$$1 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (|P_i - \bar{O}| + |O_i - \bar{O}|)^2}$$

was used to evaluate model performance, where p is the predicted value, o is the observed value and n is the number of data points. The index of agreement is a standardized measure of the degree of simulation error with 1 being a perfect match. The Index of Agreement between measured and modeled water level and current speed was 0.98 and 0.81 respectively.

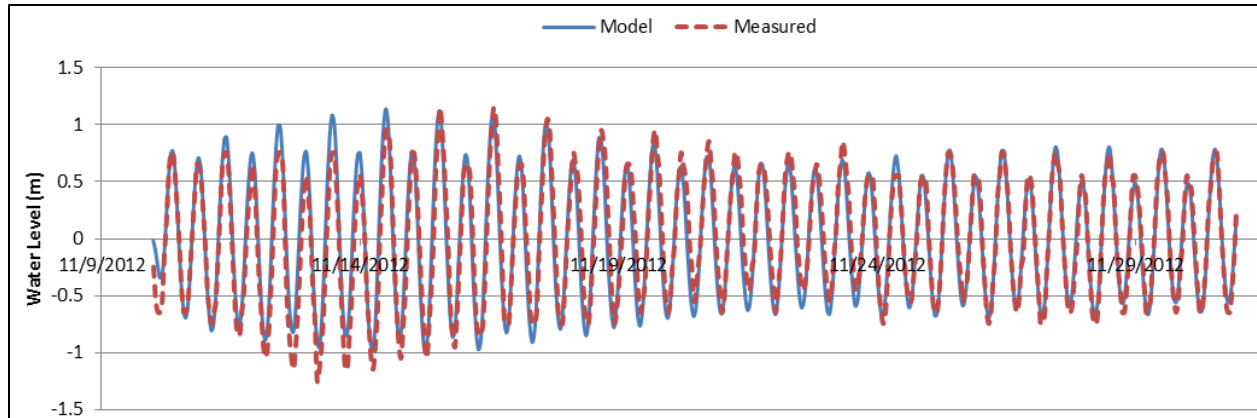


Figure 22-Comparison of modeled and measured water level at RSMS-S

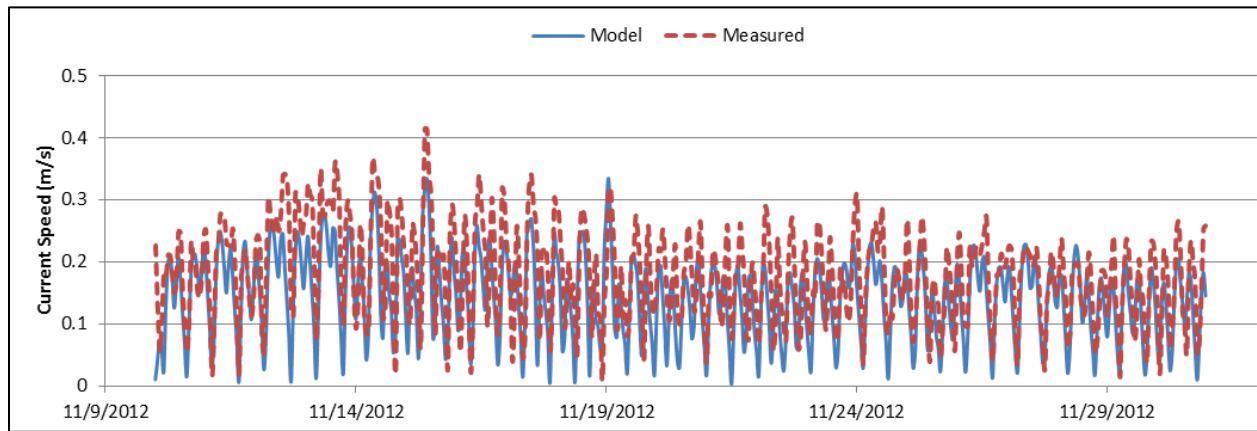


Figure 23-Comparison of modeled and measured current speed at RSMS-S

The CMS wave model was forced with wave parameters extracted from the wave data collected every 3 hrs at the offshore ADCP (figure 8) during November 9-30, 2012. Also, the model was forced with wind speed and direction every 3 hrs at NDBC 41029

Measured wave data, which matched the times of the incident wave conditions, were extracted at RSMS-S to compare with modeled data. Figure 24 shows the comparison between measured and modeled wave height at RSMS-S ADCP during November, 2012. The agreement between the measured and calculated wave data was evaluated by the Model Performance Index (MPI):

$$MPI = 1 - \frac{Error_{RMS}}{Change_{RMS}}$$

$Error_{RMS}$ is the Root Mean Square (RMS) of the model compared to measured data:

$$Error_{RMS} = \sqrt{\frac{1}{N} \sum_{i=1}^N [Y_i - X_i]^2}$$

Where N is the number of data points, Y is the modeled parameter and X is the measured parameter, and $Changes_{RMS}$ is the RMS change from the offshore data to the nearshore data:

$$changes_{RMS} = \sqrt{\frac{1}{N} \sum_{i=1}^N [X_{incident} - X_i]^2}$$

Values of MPI near unity indicated good agreement (Smith, 2000). The wave height MPI was 0.82 at RSMS-S.

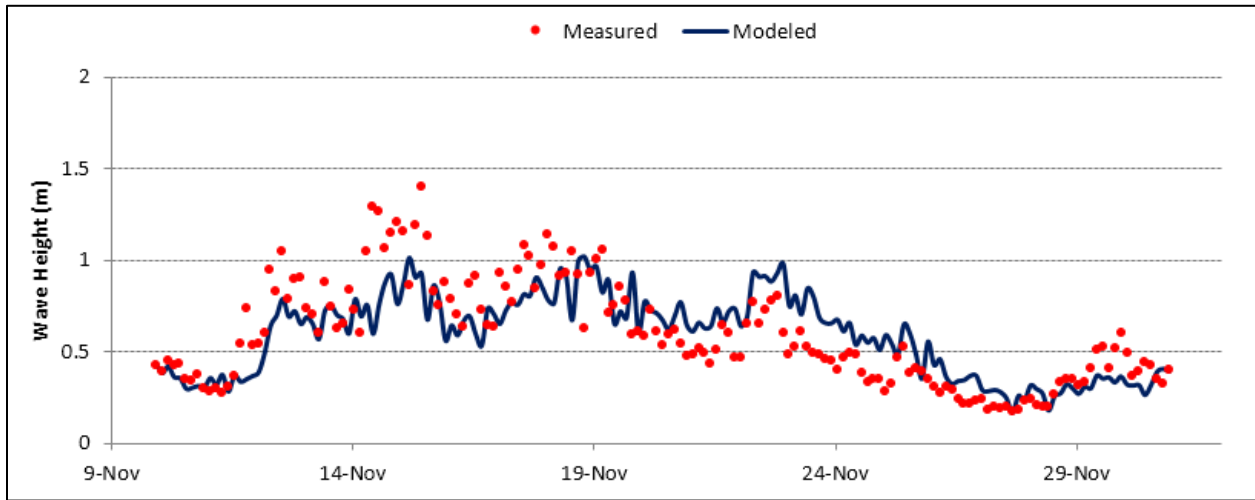


Figure 24- Comparison of modeled and measured wave height at RSMS-S

4.3 Hydrodynamic Model Validation

The current data collected during April-June of 2012 by USGS is used to validate the CMS-Flow model. Current measurements were collected by ADCPs at the five locations in the harbor and the Ashley, Cooper, and Wando Rivers, as shown in figure 25 (USACE, 2015). The G-25 station data was measured by a bottom-mounted upward-looking ADCP located at 32° 45' 04" N and 79° 51' 52" W. This instrument continuously measures currents through the entire water column.

CMS-Flow model simulation was conducted during April 12-May 12 of 2012. The model was forced with wind data at NOAA 8665530 station. Figure 26 shows the comparison between measured and modeled water level at G-25 station during April 12- May12, 2012. The modeled water level was compared to measured data at NOAA station 8665530. The Index of Agreement between measured and modeled water level was 0.97. Figures 27 and 28 show the comparison between measured and modeled current speed and direction at G-25 station respectively. The Index of Agreement between measured and modeled current speed was 0.86. The model validation indicated that the model reproduction of the water level and current is sufficiently accurate for investigating changes in the hydrodynamics due to channel deepening of the Charleston Harbor Channel.

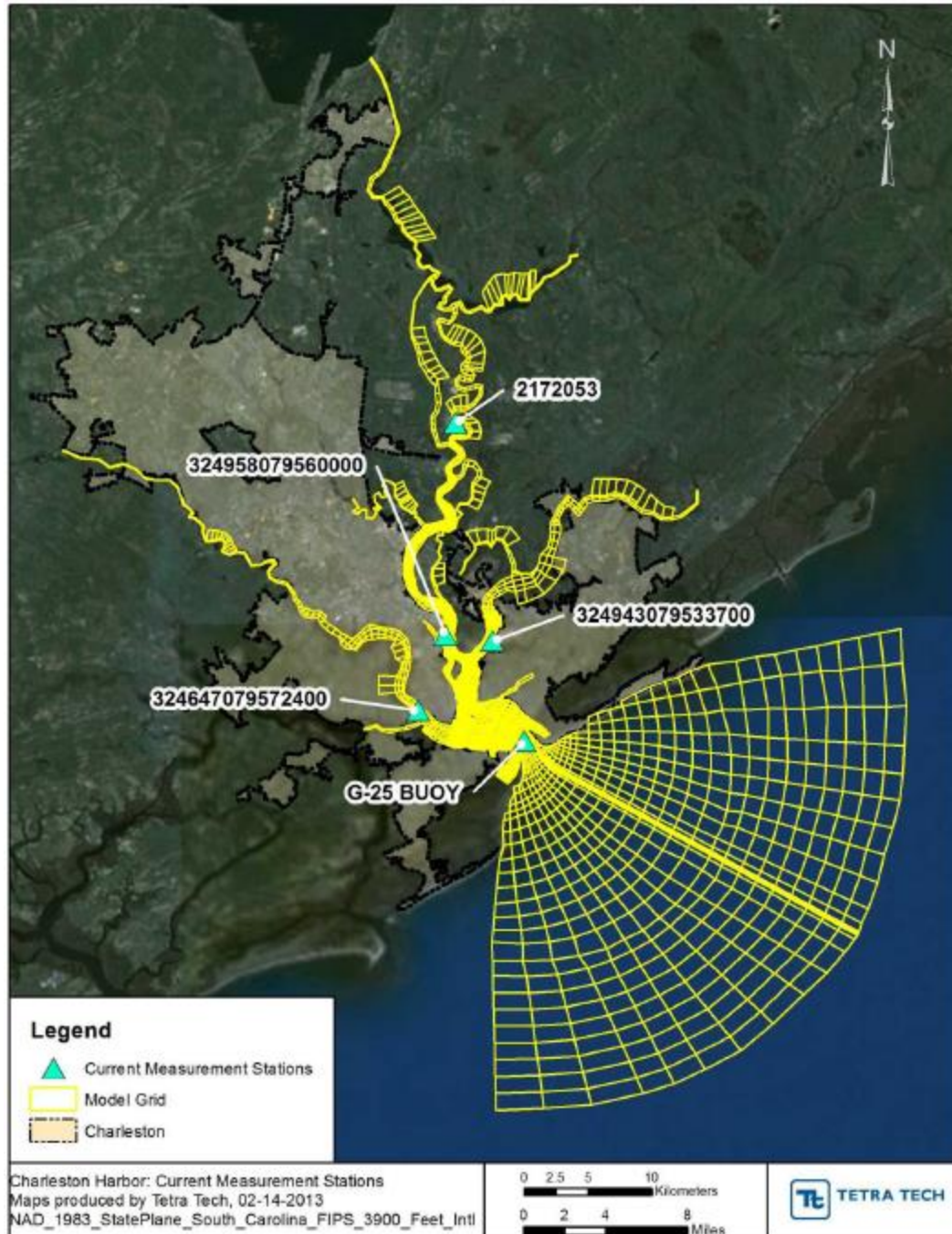


Figure 25- Continuous Current Measurement Locations for 2012 (USACE, 2015)

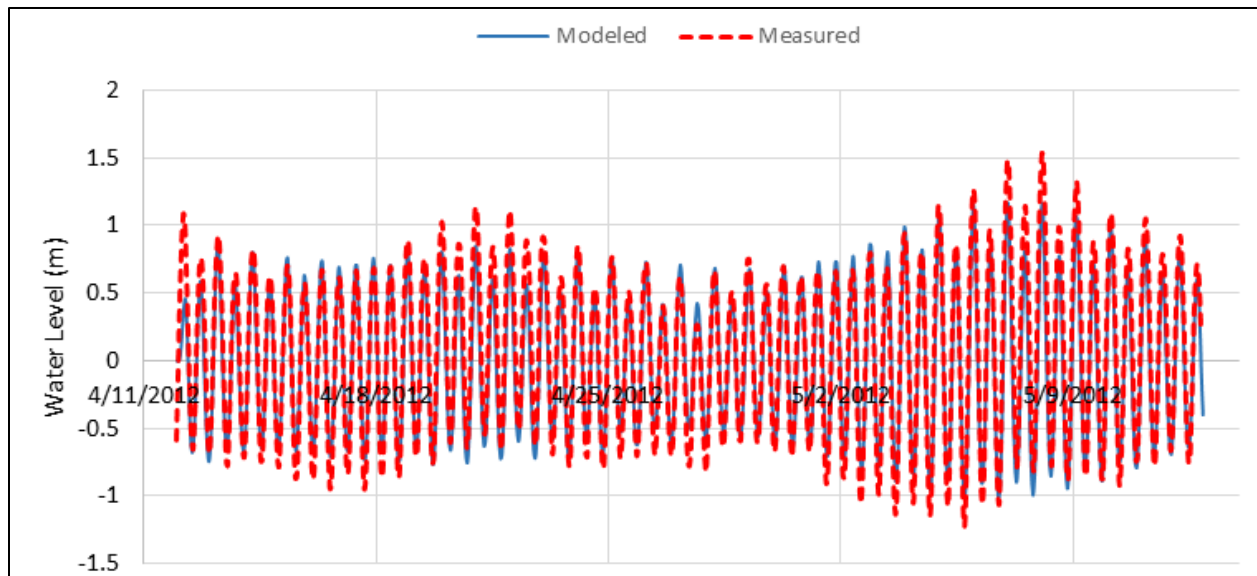


Figure 26- Comparison of modeled and measured water level at G-25 station

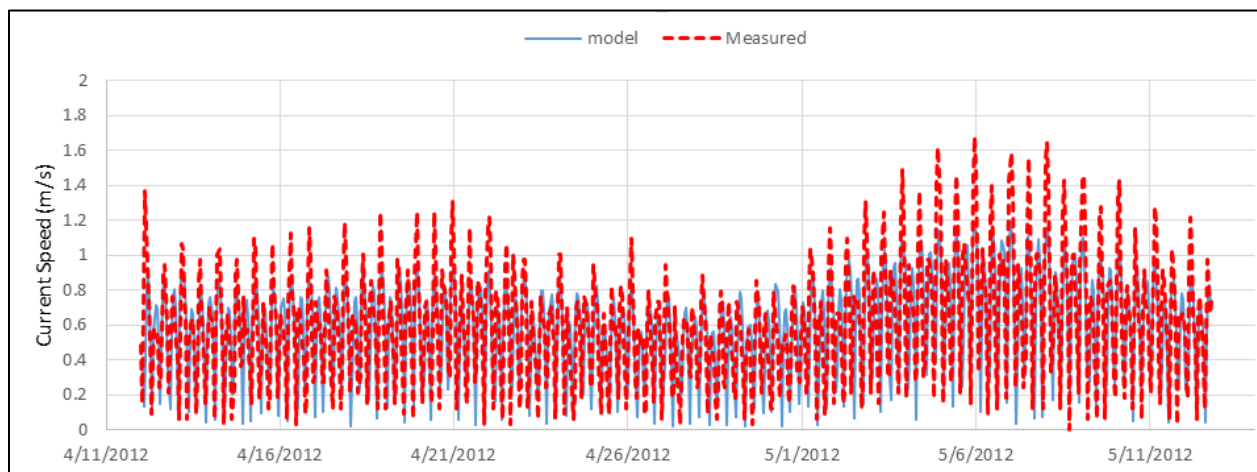


Figure 27- Comparison of modeled and measured current speed at G-25 station

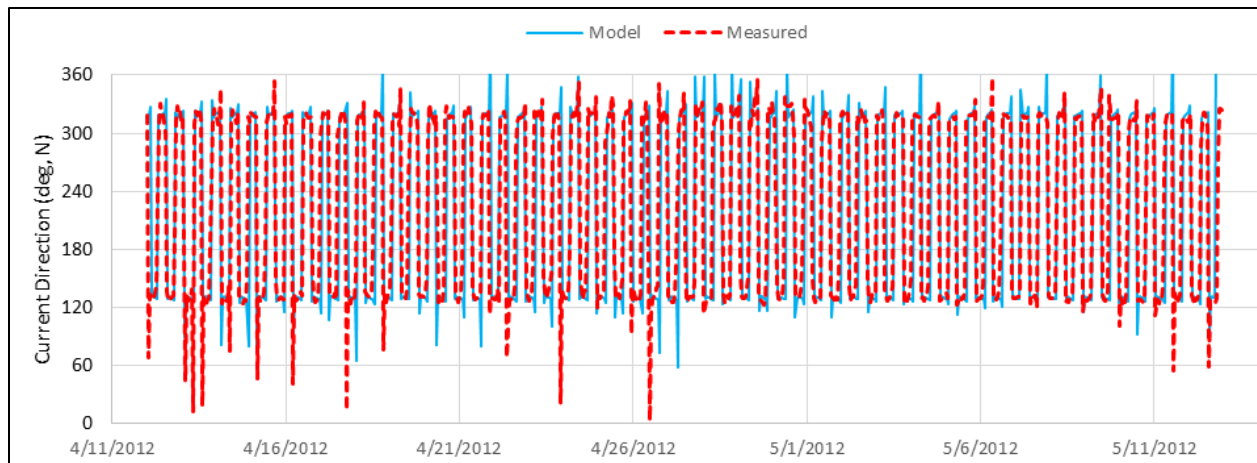


Figure 28- Comparison of modeled and measured current direction at G-25 station

4.4 Sediment Model Calibration

Sediment transport and morphology change is estimated through coupling of the CMS flow, wave and sediment models using the Steering Module. Steering refers to the coupling process between CMS-Flow and CMS-Wave models. The inline CMS contains both CMS-Flow and CMS-Wave and performs the coupling process internally. This means that both CMS-Flow and CMS-Wave are contained within a single code or executable. Even though CMS-Flow and CMS-Wave use different grids, the two models are in a single code which facilitates the model coupling and speeds up the computation by avoiding communication files, variable allocation and model initialization at every steering interval. In the steering process, the wave model is run twice at time zero to the first steering interval. The wave information is then interpolated on to the flow grid and the flow model is run from time zero to the first steering interval. The flow information is then interpolated on the wave grid and the wave model is run for the second steering interval and the process is repeated until the simulation is complete. The CMS-Flow 2-D implicit-scheme version was used for hydrodynamics and sediment transport modeling, and coupled with the CMS-Wave. The input spectra need to be spaced at regular time intervals and begin at the same time as the CMS-Flow model. The inline CMS was launched from a command line with arguments specifying the input files and steering options (Sanches et al., 2014). A steering interval of 3 hrs is adopted in this study.

The performance of the CMS sediment model is assessed based on the observed morphology trends in the area and by reproducing measured morphology change of available survey data collected during relatively short period. The survey data during 2012 and 2013 were examined and the June 25 and December 3 of 2013 surveys along the Entrance Channel were selected to compare measured and modeled morphology change. The Entrance channel was not dredged during that period.

Directional wave data was not available at the forcing offshore ADCP during the complete simulation period (June-December of 2013) and accordingly, the ODMDS ADCP (figure 8) wave data was used to force the model during June-December of 2013. Therefore, the offshore

boundaries of the CMS flow and wave models were moved landward toward the ODMDS ADCP location. Since, the CMS flow and wave grids were modified, the modeled water levels were validated during a spring tide (November 14 – 16, 2012) which demonstrates relatively active wave climate during November 2012. Figure 29 shows the incident wave height and direction during the 5 days period of November 13-17 of 2012 at the deep ocean ADCP. Figure 30 shows modeled and measured water level data at the RSM-S ADCP during the 5 days period. In general, the modified models are reproducing the water level and at the RSM-S ADCP.

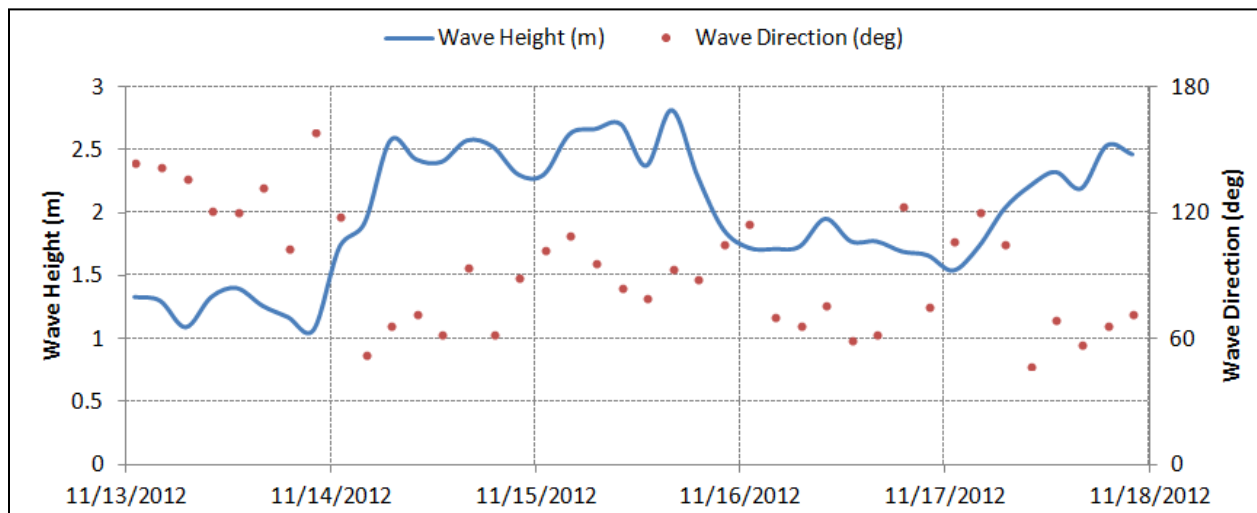


Figure 29- Wave height and direction during November 13-17, 2012

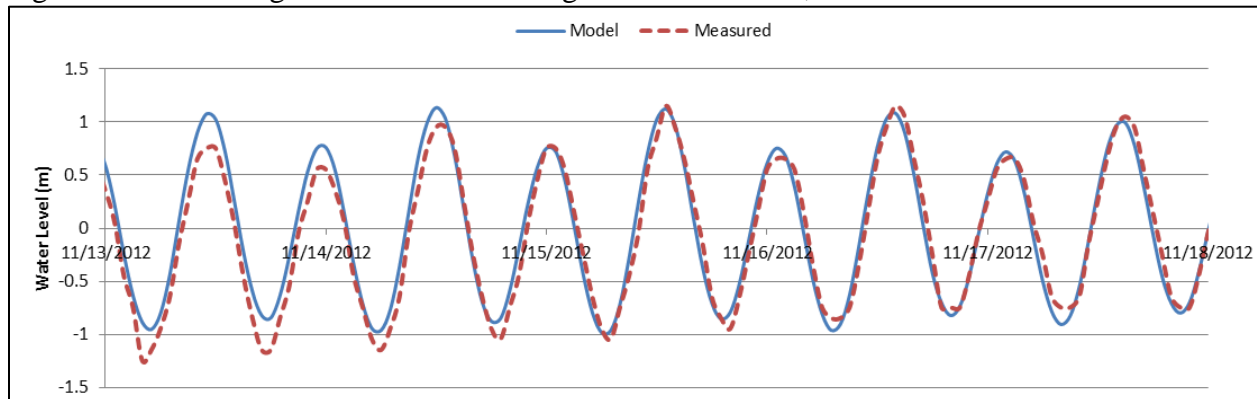


Figure 30- Comparison of measured and modeled water level at RSM-S ADCP

Sediment transport calibration was conducted as the comparison of measured and calculated morphology change during the time period extending from the June 25 to December 3 of 2013 along the Entrance Channel.

The June 25 and December 3 surveys had low resolution coverage of the Entrance Channel. To minimize interpolation inaccuracies especially around the boundaries, an area was delineated (red box) around the June 25 and December 3 surveys as shown in figure 31.

The Non-Equilibrium Transport (NET) model, which is based on a total load advection-diffusion approach was adopted to estimate sediment transport. The Lund-Cirp, van Rijn and Watanabe transport formula were examined. The van Rijn was used as the governing empirical formulas to calculate bed load and suspended load within CMS-Flow for combined waves and current.

The D50 values obtained from SAC and usSEABED were examined to accurately represent the spatial distribution of sediment within the model domain. The available grain sizes and their locations were used as guidance to specify the D50 spatial distribution within the CMS-Flow grid. A spatially variable grain size between 0.07-0.18 mm was adopted in the CMS-Flow model (USACE, 2013). To obtain acceptable agreement between the modeled and measured morphology change, the distribution of the D50, adaptation length and the sediment transport grain size parameters were tuned to get the best agreement between measured and modeled morphology change (reasonably reproduce measured morphology change). The default CMS scaling factors were not modified and the transport grain size parameter which represents the median grain size of the surface layer was selected as 0.15 mm in the CMS-Flow model control. Table 4 shows the sediment transport parameters adopted for this study.

A Darcy-Weisbach friction coefficient of 0.007 and diffraction intensity of 4 were adopted for the CMS-Wave model.

Beck and Legault (2012) stated that modeled results were filtered for morphology change within a range of +1 m, which is considered well within the error of morphologic modeling. Both the model predictions and the survey data suggest minimal change within the delineated area as shown in figure 32. The model validation indicated that the model was sufficiently accurate for investigating relative changes in the morphology change due to channel deepening of the Charleston Harbor Navigation Channel.

Table 4- CMS-Flow setup parameters

Parameter	Value
Solution scheme	Implicit
Simulation duration	6 months
Ramp period	10 hr
Hydrodynamic time step	15 min
Steering interval	3 hrs
Transport formula	VanRijn
Bed load scaling factor	1.0
Suspended load scaling factor	1.0
Total-load adaptation length	10 m
Morphologic acceleration factor	1.0
Bed porosity	0.4
Bed slope coefficient	1.0
Sediment Transport grain Size	0.15 mm

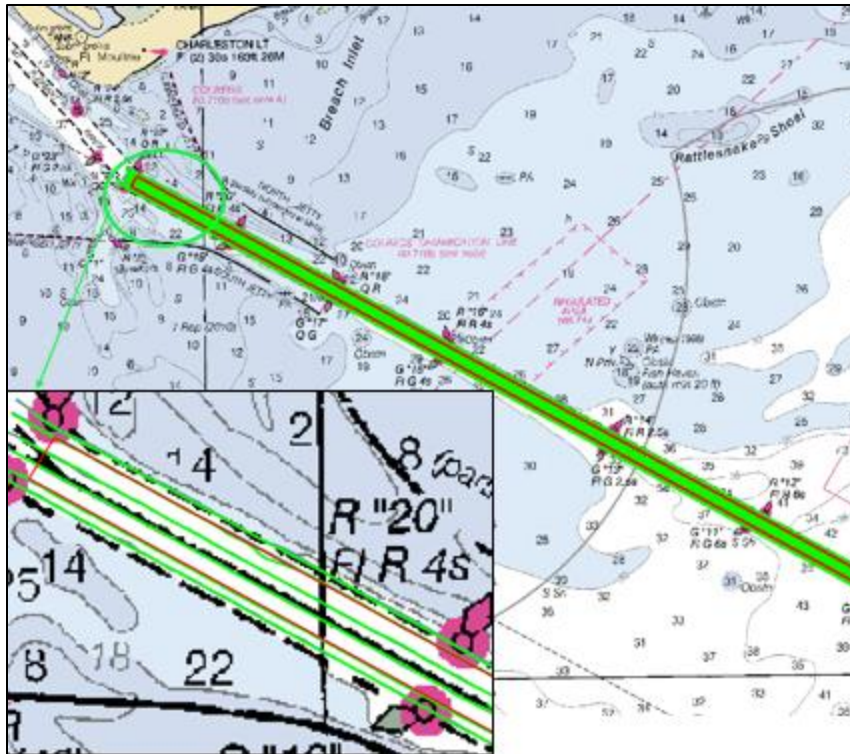


Figure 31-Entrance channel surveys and delineated area used for the sediment model calibration

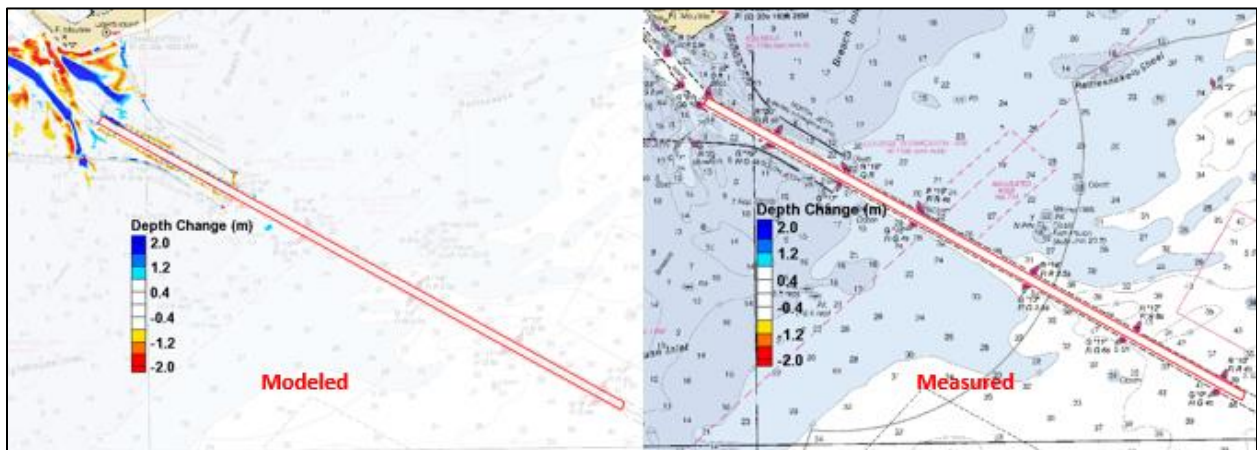


Figure 32-Modeled and measured depth change between June 25 and December 3 of 2013 surveys

5. MODELS SIMULATIONS PERIODS

The calibrated CMS models are used to determine effects to the local wave and current conditions caused by the proposed channel deepening. In addition, the models address change in morphology in the area for the future with project scenario. The modeling simulations includes

long-term and extreme short term periods. Field data collected during a previous Charleston Harbor numerical modeling study (EPA, 2014) which included nearshore current and wave measurements, were used in the present modeling work. The active winter weather month of December of 2012 was selected as the long-term period. Figure 33 shows time series of wave height, at the Offshore ADCP, during December, 2012. The figure also shows wind speed time series during the selected simulation period. Hourly wind data was obtained from NDBC 41029 station. The maximum measured offshore wave height was 3.56 m and occurred on December 26 at 19:00.

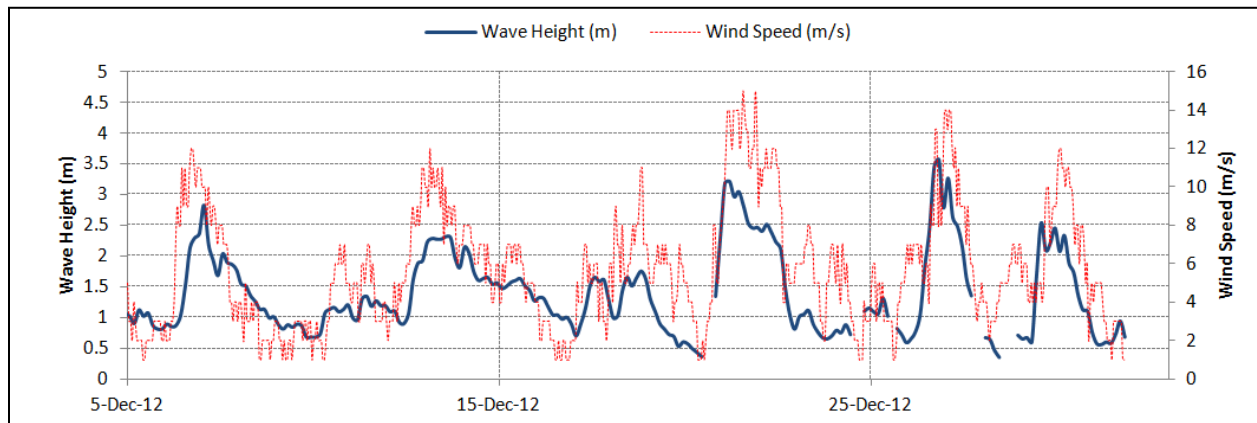


Figure 33- Wave height, at the Offshore ADCP, during the active winter simulation period

Figure 34 shows that the only storm observed, within SC, during 2013 was Tropical Storm Andrea (Jun 6-7). Tropical storm Andrea is selected to represent the extreme short term simulation period. EPA (2015) examined the most intense storms to represent the wave and flow climate at the Charleston ODMDS during the EPA ADCPs measurement duration (November 2012-August 2013). Figure 35 shows the wave height, current speed and direction during storm Andrea. The maximum offshore measured wave height was 4.3 m and occurred on June 7 at 10:00.

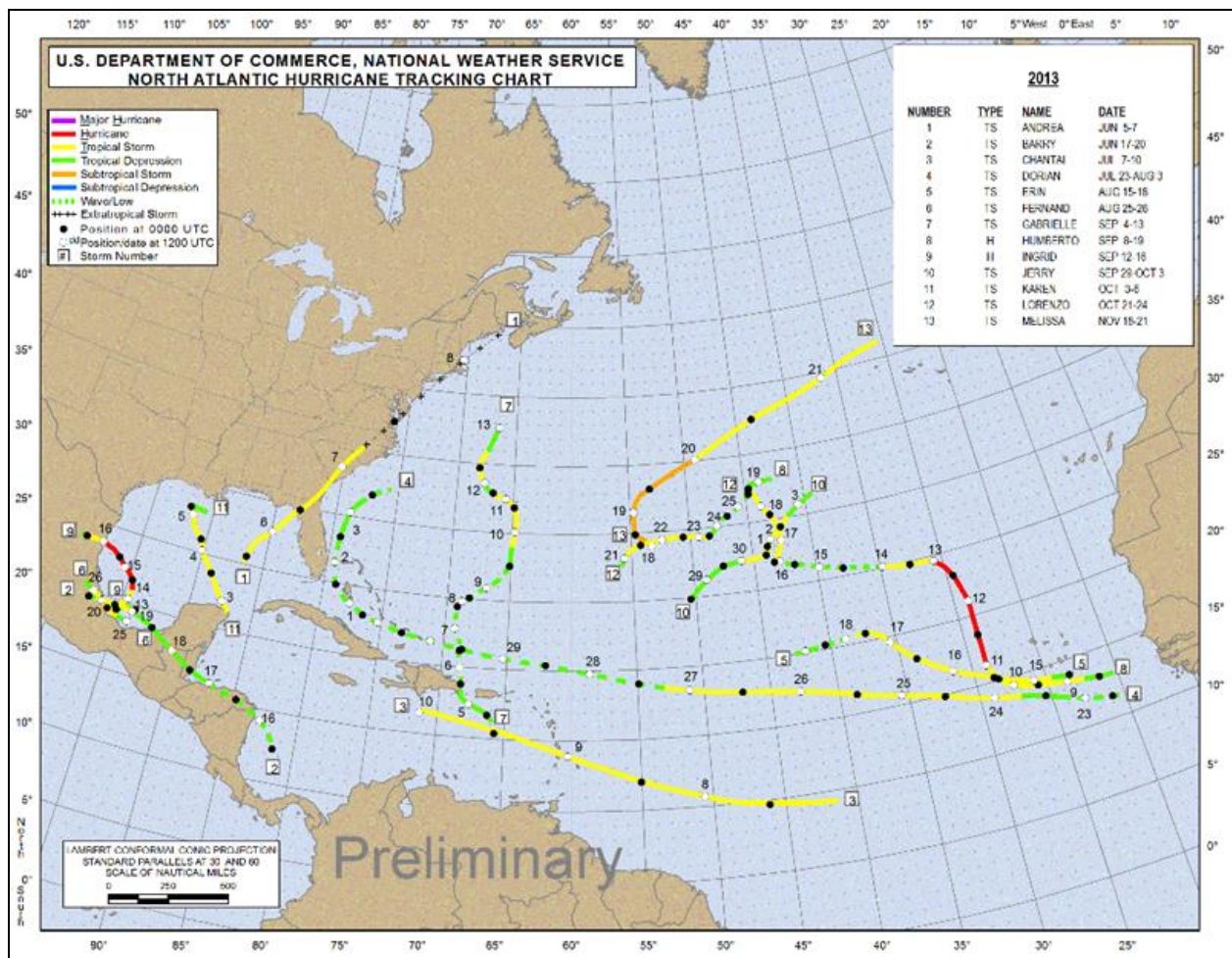


Figure 34- 2013 North Atlantic Hurricane Tracking Chart

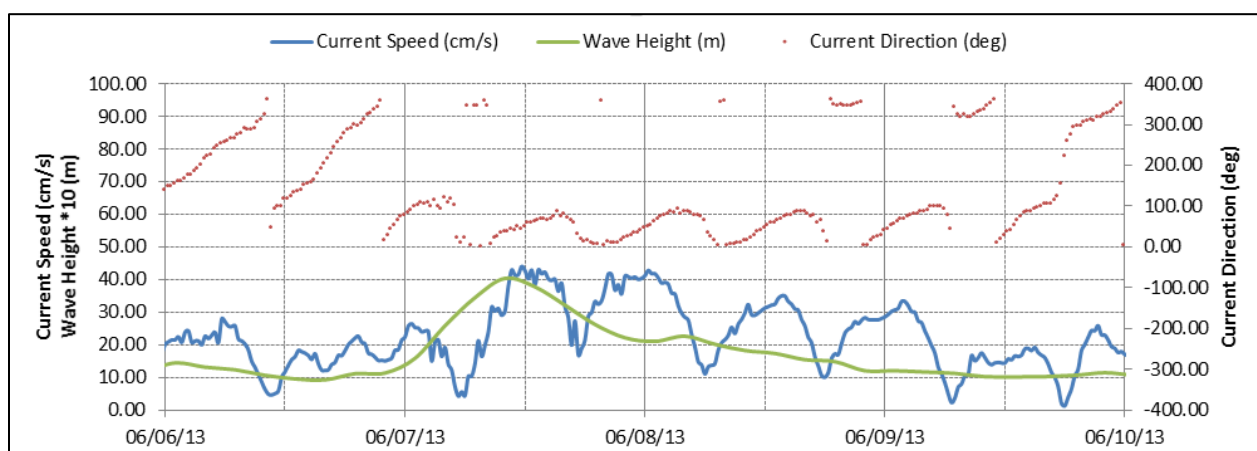


Figure 35- Wave height, current speed and direction during storm Andrea

6. EVALUATION OF BASE CONDITIONS

The base conditions in this study are an estimate of possible conditions that may exist at the approximate time that the project is completed. USACE (2015), Charleston Harbor post-45 feasibility study, stated the start date of project as 2022. Therefore, the base year conditions are defined based on the expected bathymetric, hydrologic and SLR conditions in year 2022.

The CMS flow and wave grids were modified by assigning a depth of 51 feet MLLW in the entrance channel, and 49 feet MLLW from Mount Pleasant Range throughout the federal navigation channel in Charleston Harbor, Wando River, and Cooper River. All depths assigned to the federal navigation channel include the design depth of 47 feet for the entrance channel and 45 feet throughout the navigation channel plus 2 feet overdrudge and 2 feet advance maintenance USACE (2015). The bathymetry for the base condition in the Charleston Harbor Channel was set as the deeper of the existing conditions bathymetry or the elevation corresponding to the design depth in each channel grid cell. The scatter data set used to create the Environmental Fluid Dynamics Code (EFDC) multifunctional surface water modeling system software existing conditions was used to modify the depth within the navigation channel for the base condition.

USACE (2015b) stated that because weather, hydrology, and operating conditions cannot be predicted years in advance, water conditions for Base and Future years were developed using available existing forcing conditions but modified to account for SLR. For this study, the forcing conditions for the selected simulation periods were modified to reflect the increase in SLR.

The rates of sea level change relative to Charleston Harbor, using 2012 tidal data for the analysis of existing conditions, during the base year (2022) are as follows (USACE, 2015): “low” rate of change is 0.1 feet, the “intermediate” is 0.14 feet and the “high” is 0.25 feet. CMS models simulations were conducted for the low, intermediate and high SLC scenarios during the active weather and extreme storm simulation periods.

The maximum wave height was 3.56 m and occurred at 19:00 on 26 December 2012 for the active winter month. During the extreme storm event, the maximum wave height was 4.34 m and occurred at 10:00 on 7 June 2013. Wave and current change was investigated during the peak wave conditions for the active winter month and the extreme storm event for the base, future with project and future without project conditions for the high SLC scenario.

Figure 36 shows the maximum wave height field during the active winter month for the high SLC scenario. Figure 37 shows the spatial variation of current field near the peak wave height (17:00) of the active winter month for the high SLC scenario. The figure shows flow pattern during ebb tide with maximum current speed of about 0.62 m/second in the federal navigation channel between the jetties. Figure 38 shows the morphology change at the end of the active winter month for the high SLC scenario. The warmer colors in the figure represent erosion and cooler colors represent deposition. Changes in morphology in front of Morris Island are observed in front of Cumming Pt and in front of the Island spit. Also, some change in morphology occurred in front of Fort Sumter. For Sullivan’s Island, morphology change mainly occurred in

front of Fort Moultrie. The changes in the inlet area were mainly confined within the jetties and at the Dynamite Hole area.

Figure 39 shows the maximum wave height field during the storm event for high SLC scenario. Figure 40 shows the spatial variation of current field at the peak wave height of the storm event for the high SLC scenario. The figure shows flow pattern during flood tide with current speed of about 0.85 m/second in the federal navigation channel near the harbor entrance. Figure 41 shows the morphology change at the end of the storm event for high SLC scenario. Changes in morphology in front of Morris Island are mainly observed in front of the Island spit. For Sullivan's Island, morphology change mainly occurred in the area between the navigation channel and Fort Moultrie. The changes in the inlet area were mainly confined within the jetties and at the Dynamite Hole area.

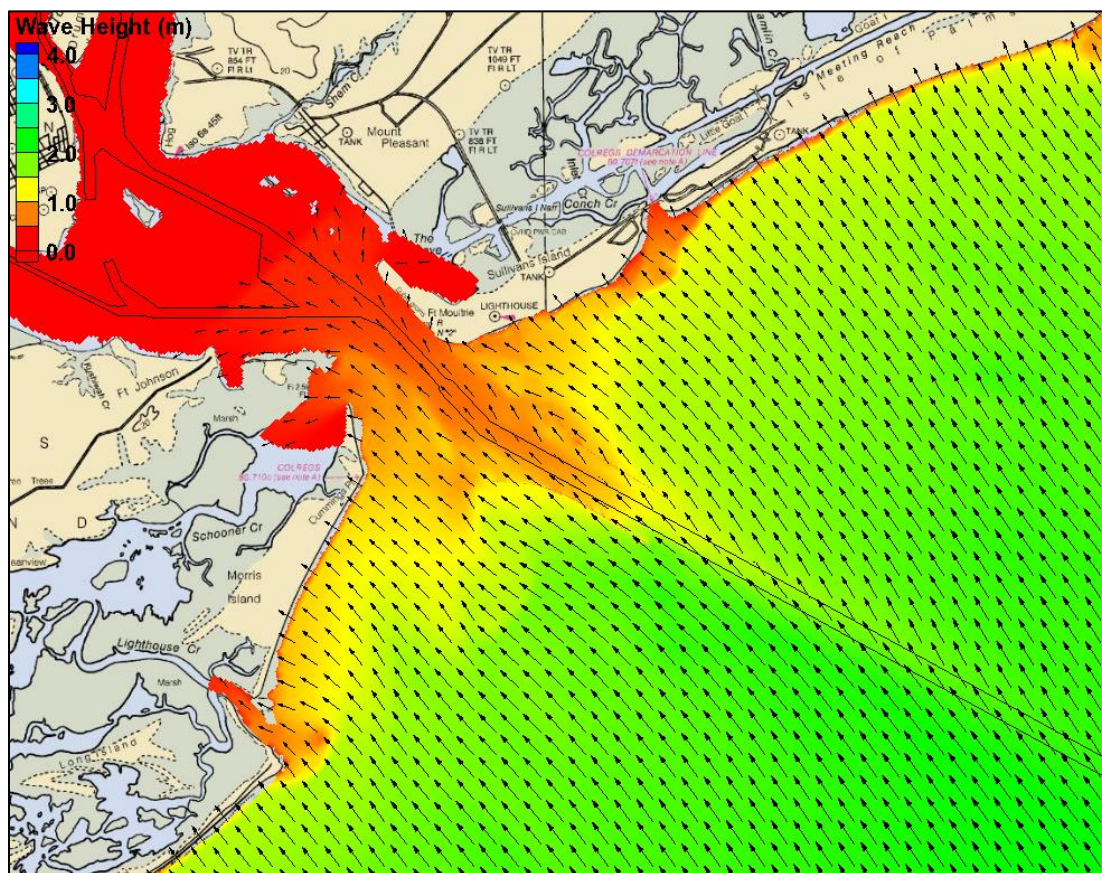


Figure 36- Base maximum wave height field during the active winter month for high SLC scenario

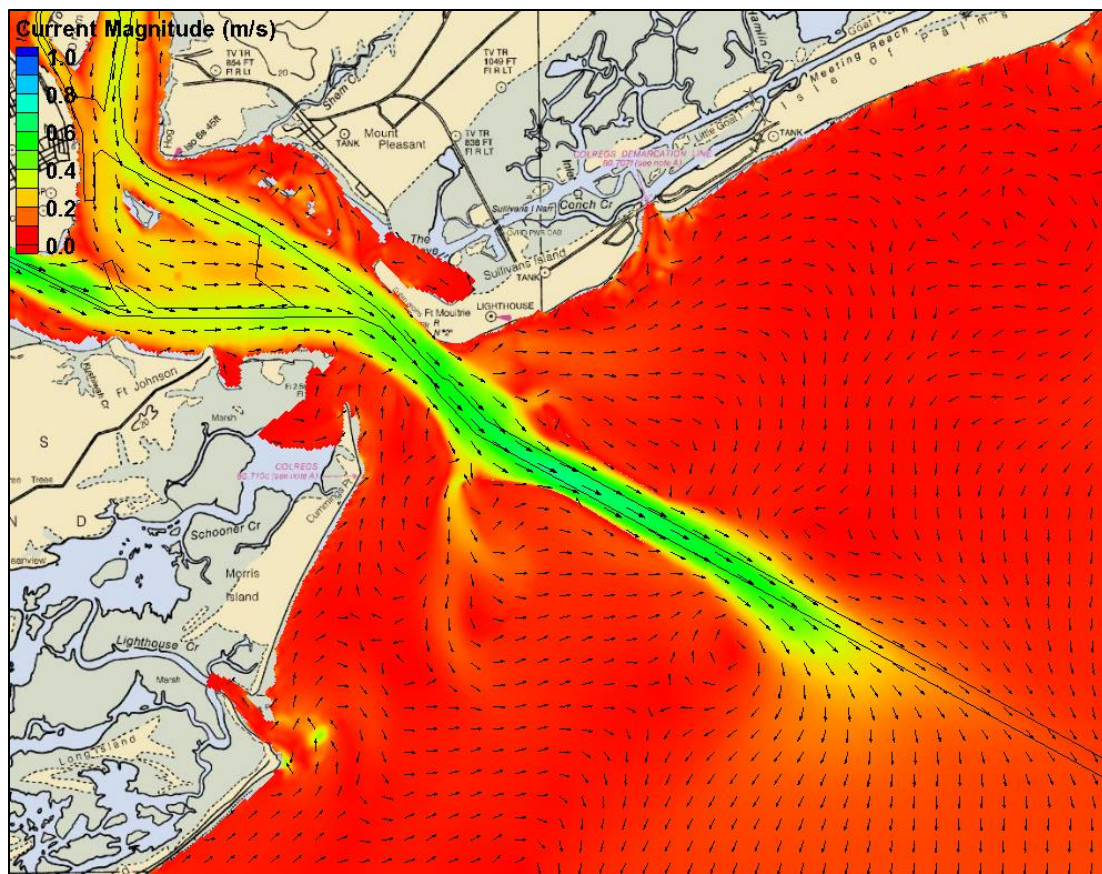
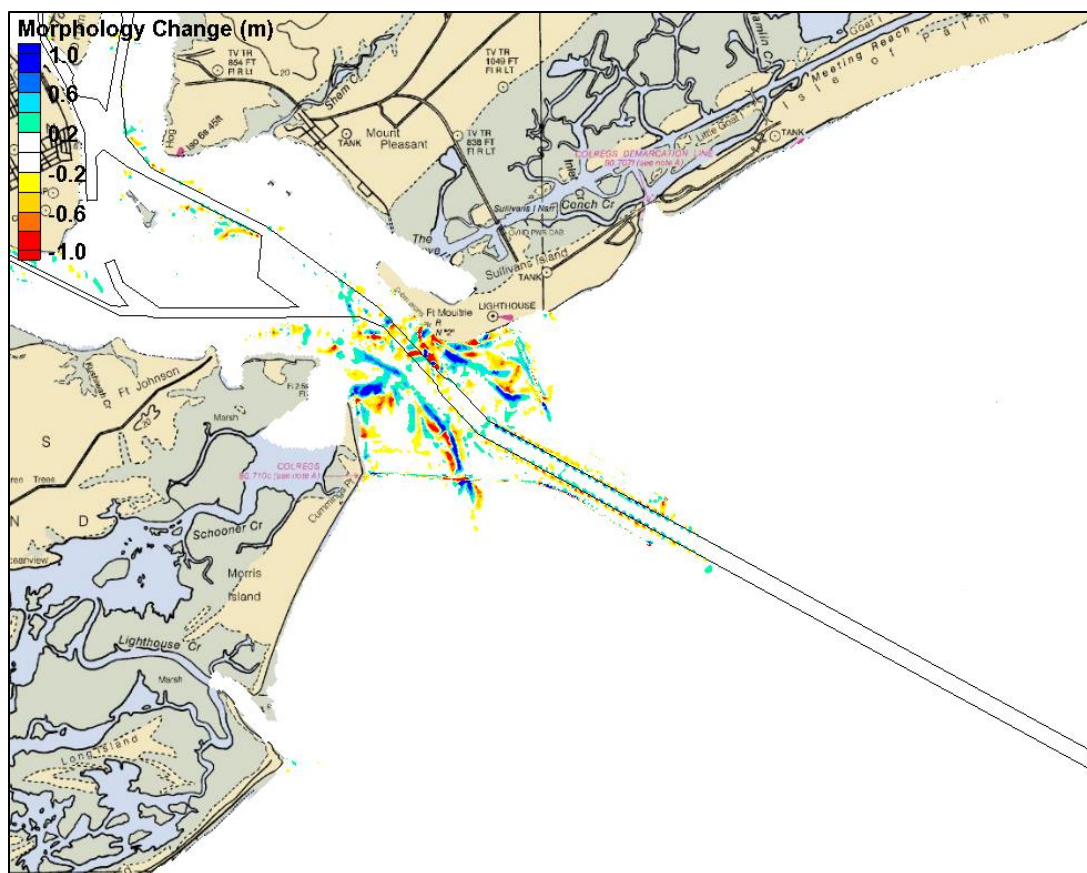


Figure 37- Base flow pattern during the active winter month for high SLC scenario



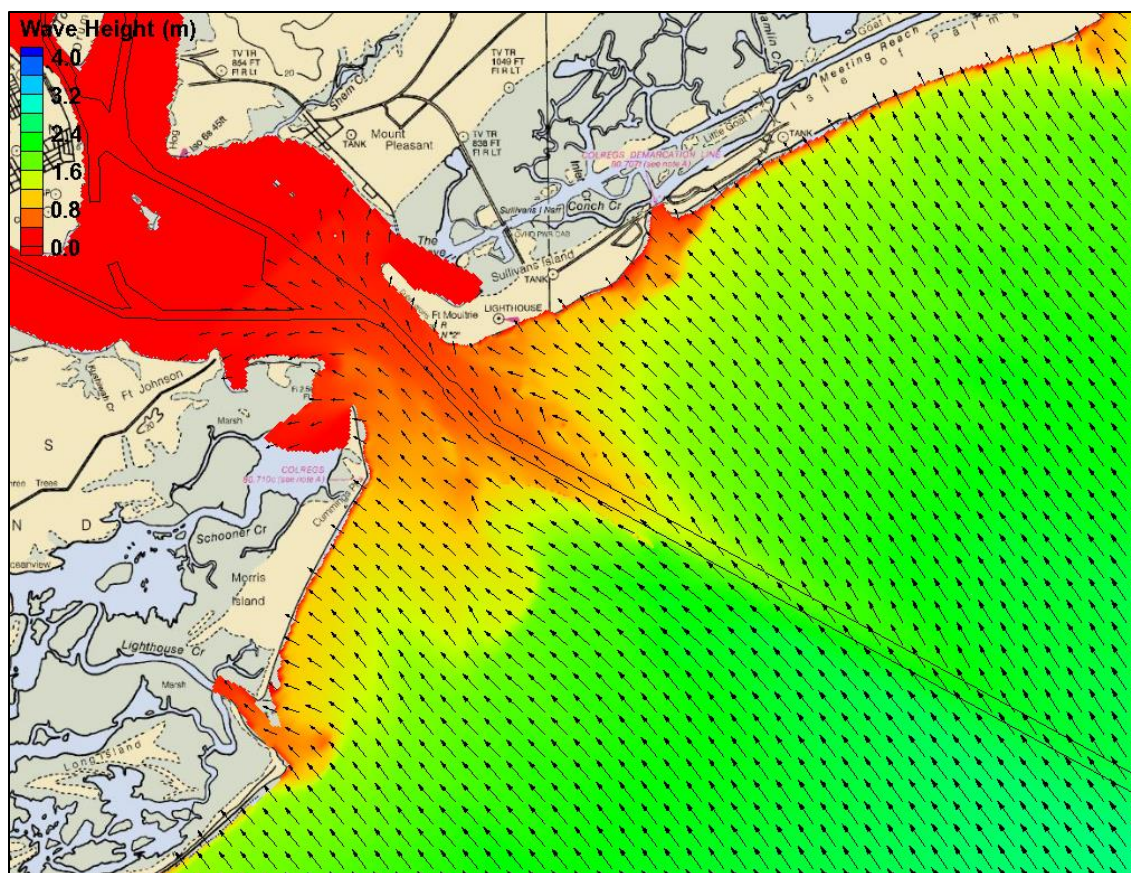
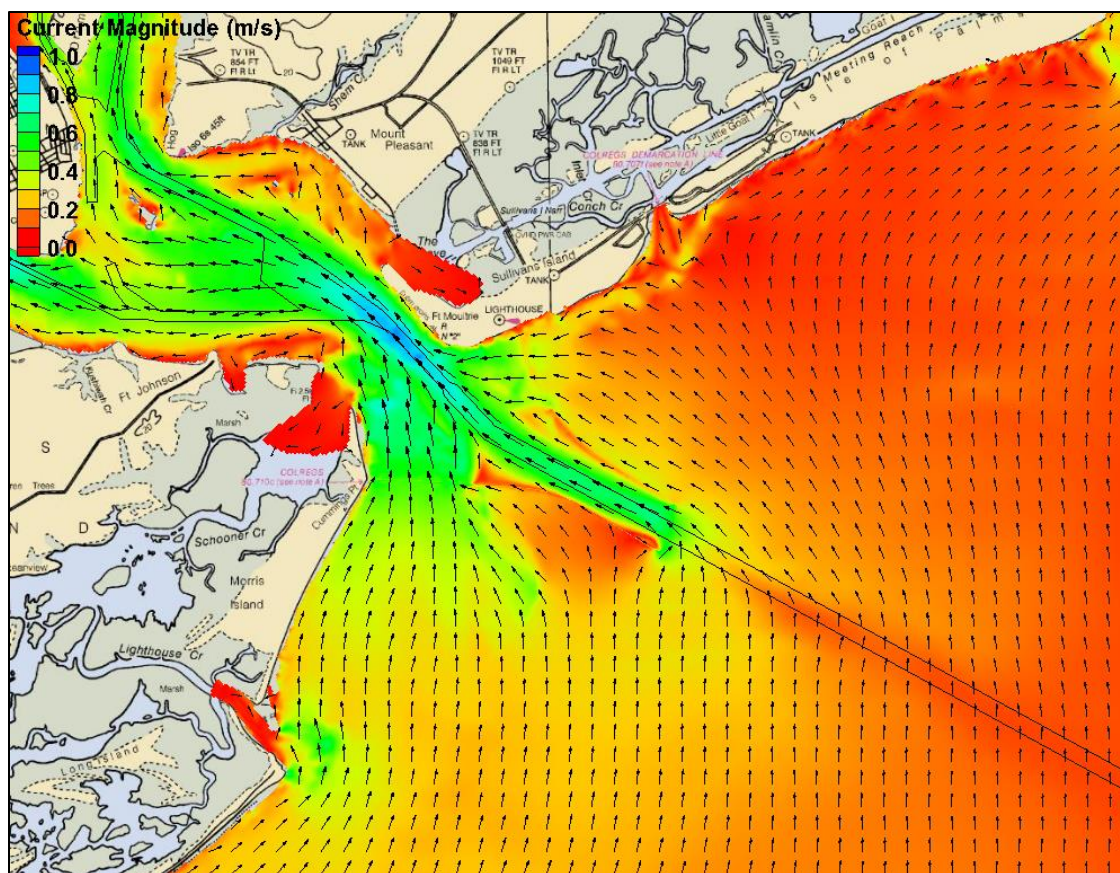


Figure 39- Base maximum wave height field during the extreme storm event for high SLC scenario



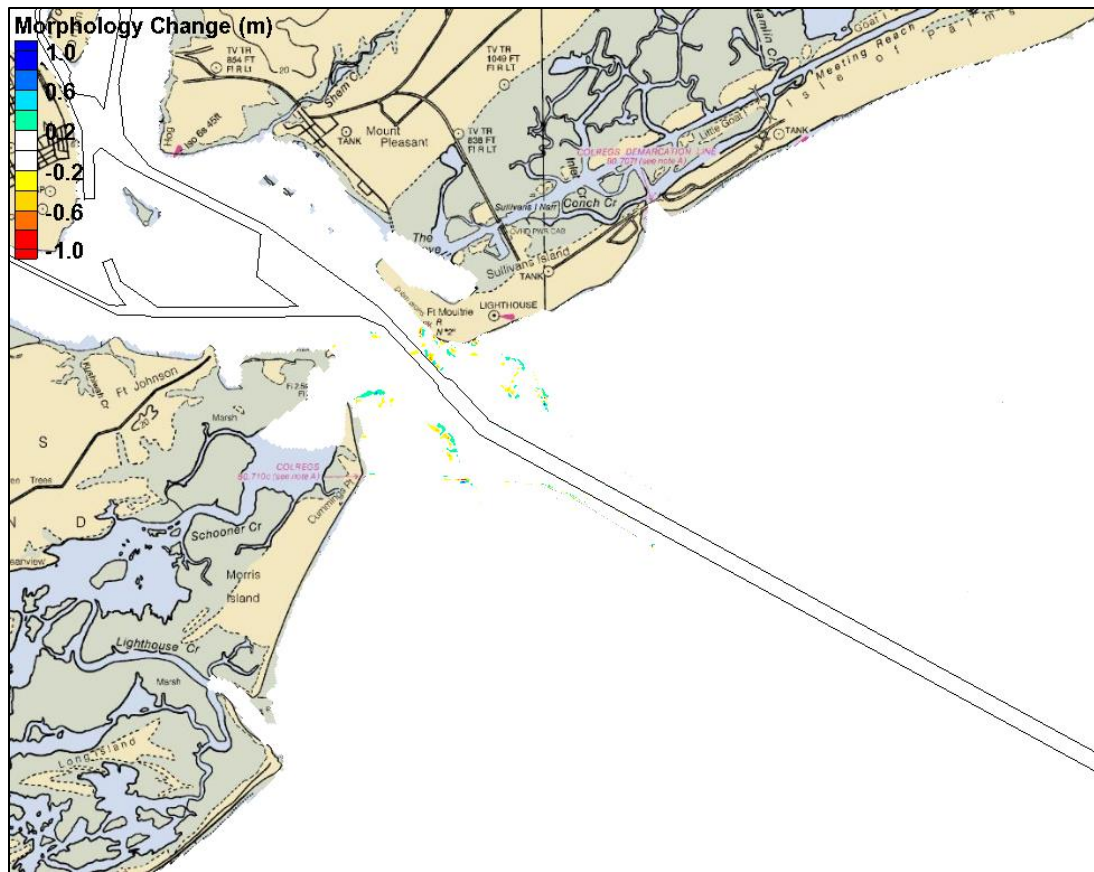


Figure 41- Base modeled morphology change at the end of the extreme storm event for high SLC scenario

7. EVALUATION OF FUTURE CONDITIONS

The FWP and FWOP conditions represent future states beginning in project year one and extending over a 50-year period of analysis. The without- project condition is the most likely condition expected to exist over the 50-year period without further channel deepening. The bathymetry for the without-project in the Charleston Harbor Channel will be set as the base conditions bathymetry.

USACE (2015) stated that future design depth is 54 feet MLLW in the entrance channel, 52 feet MLLW from Mount Pleasant range to Wando River up to Wando terminal (includes turning basin) and to Cooper River (includes turning basin). Design depth is 48 feet MLLW from Daniel Island bend to Ordnance reach (includes turning basin). The bathymetry for the with-project in the Charleston Harbor Channel is set as the deeper of the existing conditions bathymetry or the elevation corresponding to the design depth in each channel grid cell. The scatter data set used to create the EFDC future conditions was used to modify the depth within the navigation channel.

USACE (2015) used the 2012 tidal data for the analysis of existing conditions. Estimating construction completion of 2021, and a 50 year project life, starting with 2012 (thus estimate

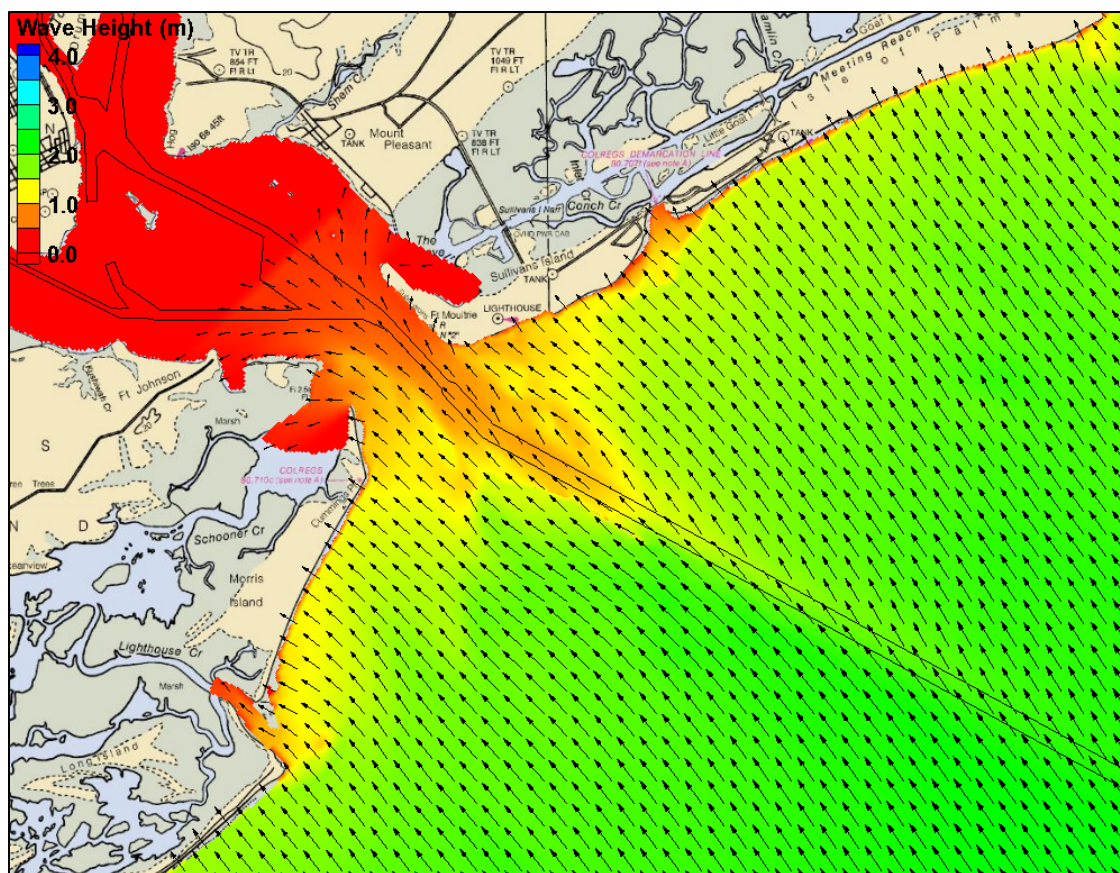
the increase in 59 years) – the rates of sea level change relative to Charleston Harbor are as follows: “low” rate of change is 0.57 feet, the “intermediate” is 1.08 feet and the “high” is 2.74 feet

SLC was included in the FWP and FWOP scenarios by adjusting the water level from the 2012 existing conditions to year 2071. CMS models were used to evaluate coastal morphology for the FWP and FWOP conditions.

7.1 Future Without Project Scenario

Figure 42 shows the maximum wave height field during the active winter month for high SLC scenario. Figure 43 shows the spatial variation of current field near the peak wave height (17:00) of the active winter month for the high SLC scenario. The figure shows flow pattern during ebb tide with maximum current speed of about 0.52 m/second in the federal navigation channel between the jetties. Figure 44 shows the morphology change at the end of the active winter month for high SLC scenario. The warmer colors in the figure represent erosion and cooler colors represent deposition. Changes in morphology in front of Morris Island are observed in front of Cumming Pt and in front of the Island spit. Also, some change in morphology occurred in front of Fort Sumter. For Sullivan’s Island, morphology change mainly occurred in front of Fort Moultrie. The changes in the inlet area were mainly confined within the jetties except at the Dynamite Hole area.

Figure 45 shows the maximum wave height field during the storm event for the high SLC scenario. Figure 46 shows the spatial variation of current field at the peak wave height of the storm event for the high SLC scenario. The figure shows flow pattern during flood tide with maximum current speed of about 0.78 m/second in the federal navigation channel near the harbor entrance. Figure 47 shows the morphology change at the end of the storm event for high SLC scenario. Changes in morphology in front of Morris Island are mainly observed in front of the Island spit. For Sullivan’s Island, morphology change mainly occurred in the area between the navigation channel and Fort Moultrie. The changes in the inlet area were mainly confined within the jetties and at the Dynamite Hole area.



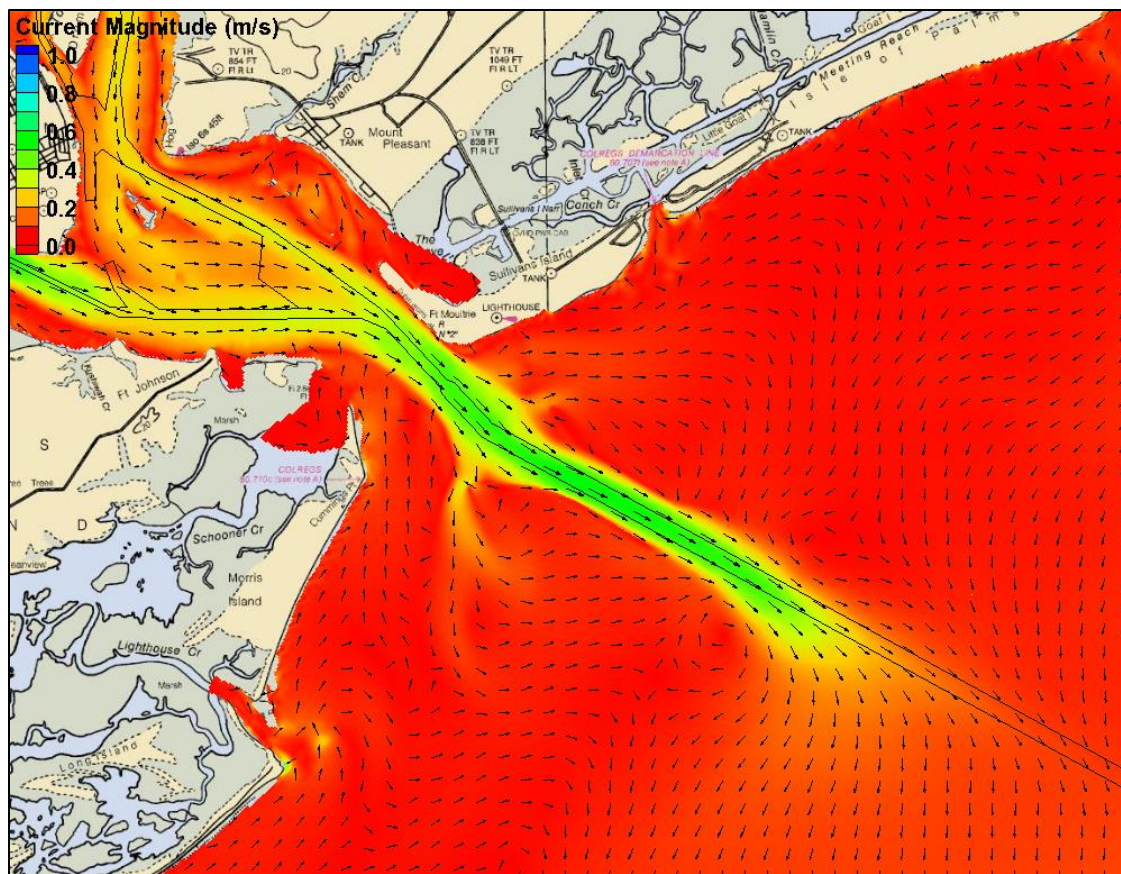
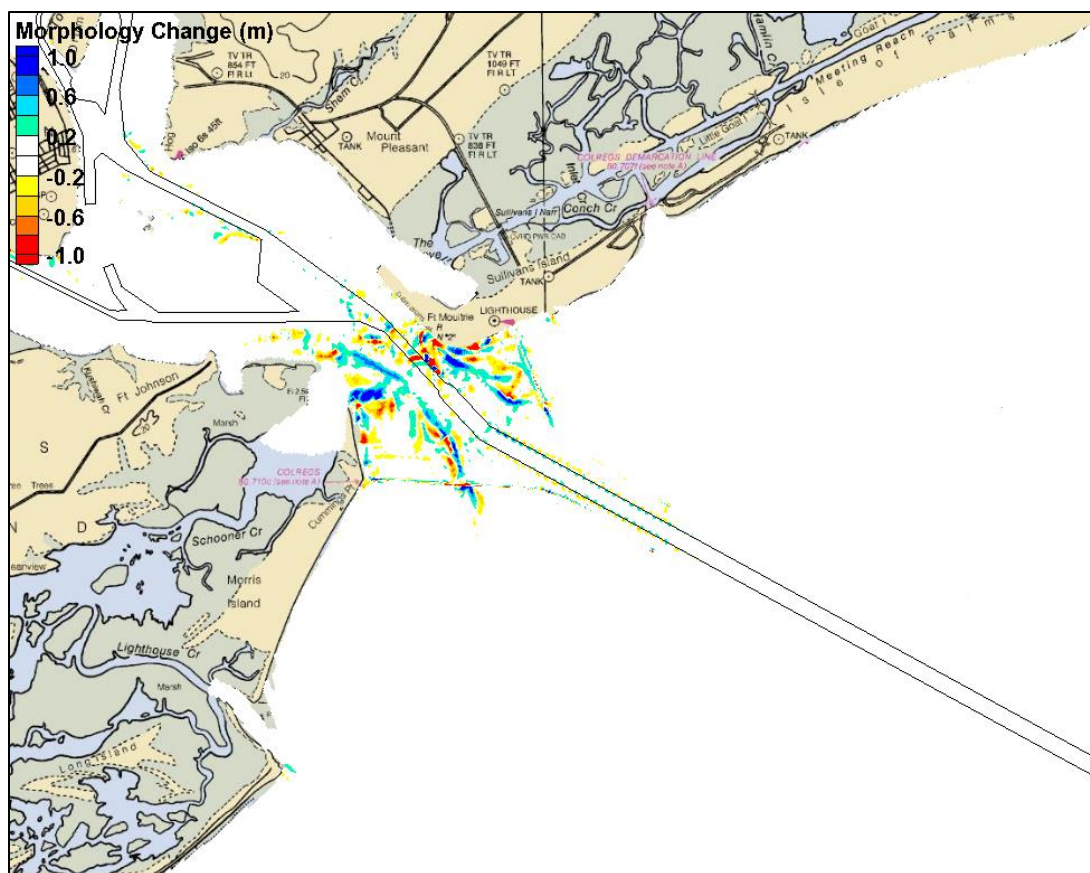


Figure 43- FWOP flow pattern during the active winter month for high SLC scenario



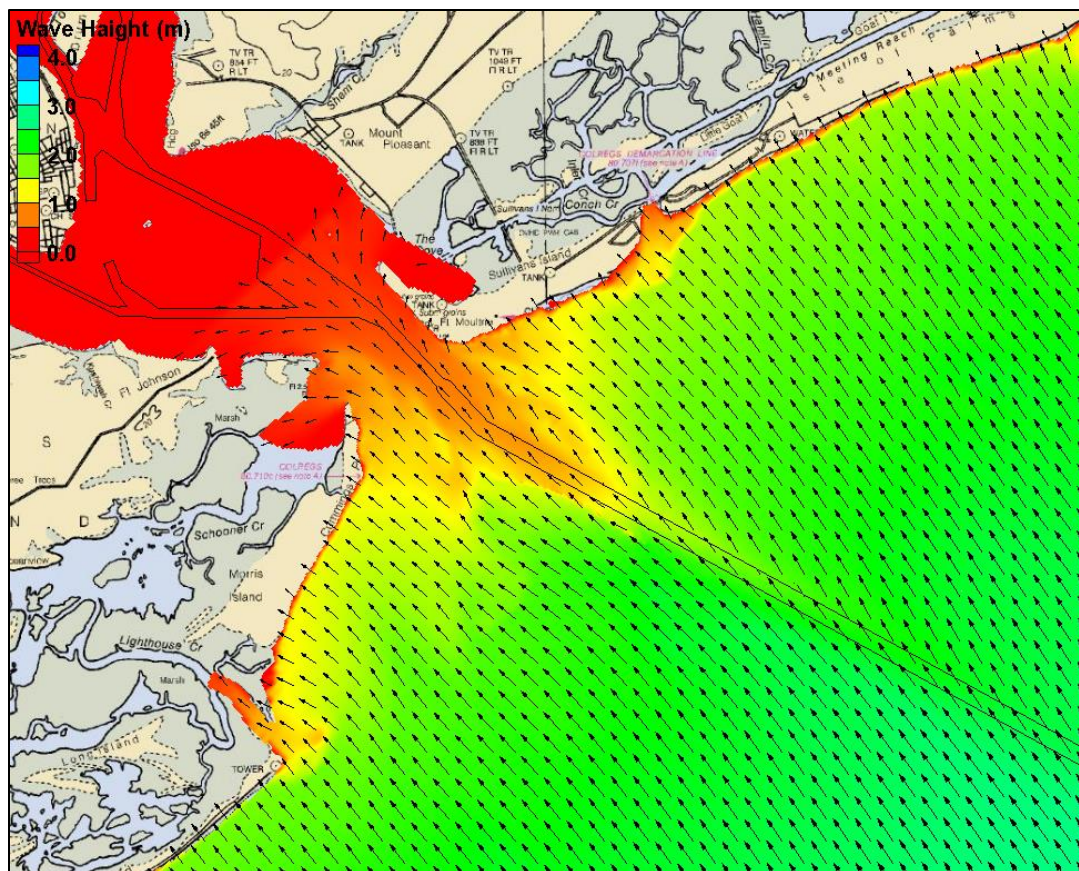


Figure 45- FWOP maximum wave height field during the extreme storm event for high SLC scenario

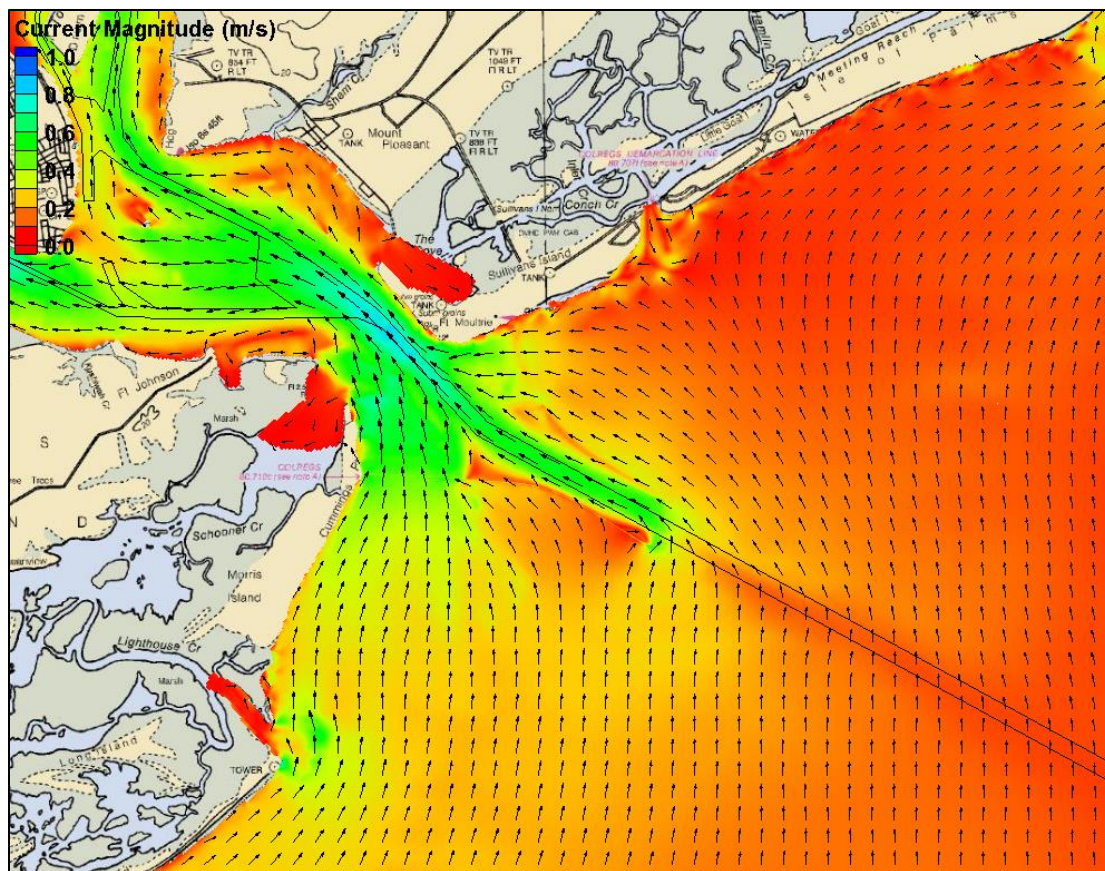


Figure 46- FWOP flow pattern during the extreme storm event for high SLC scenario

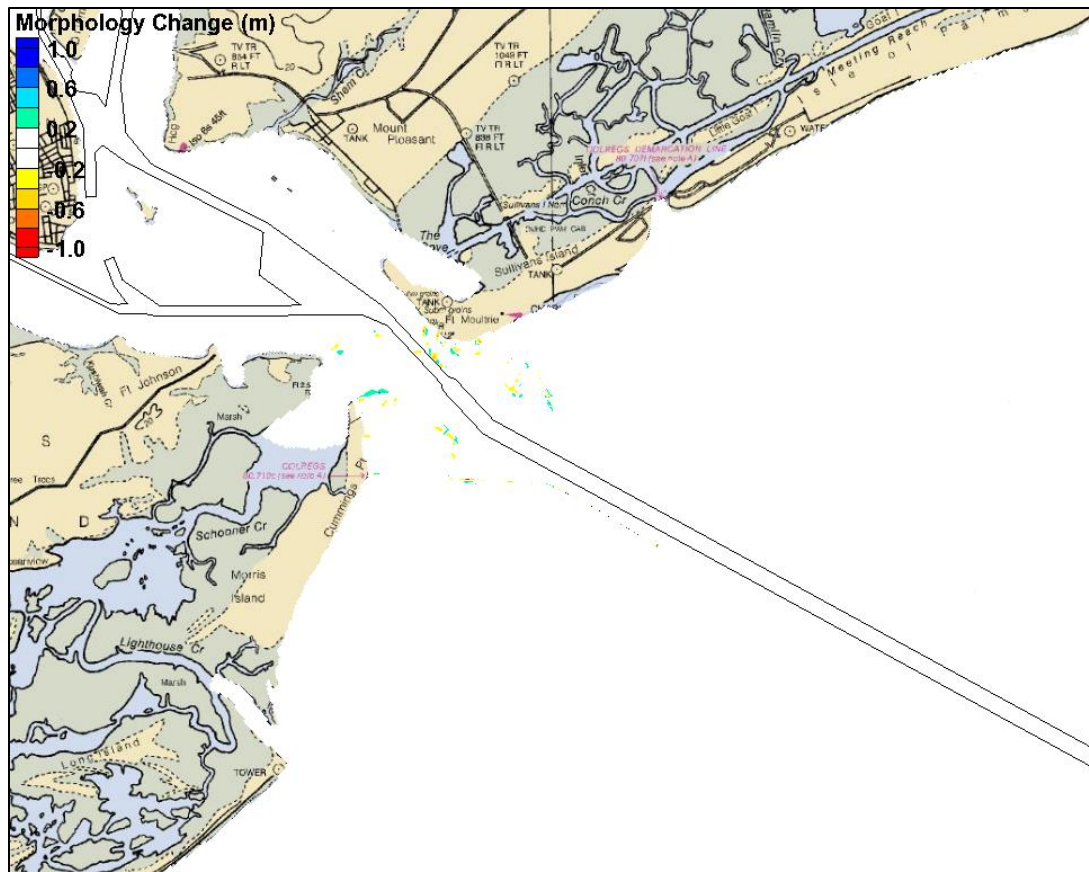


Figure 47- FWOP modeled morphology change at the end of the extreme storm event for high SLC scenario

7.2 Future With Project Scenario

Figure 48 shows the maximum wave height field during the active winter month for high SLC scenario. Figure 49 shows the spatial variation of current field near the peak wave height (17:00) of the active winter month for the high SLC scenario. The figure shows flow pattern during ebb tide with maximum current speed of about 0.51 m/second in the federal navigation channel between the jetties. Figure 50 shows the morphology change at the end of the active winter month for high SLC scenario. The warmer colors in the figure represent erosion and cooler colors represent deposition. Changes in morphology in front of Morris Island are observed in front of Cumming Pt and in front of the Island spit. Also, some change in morphology occurred in front of Fort Sumter. For Sullivan's Island, morphology change mainly occurred in front of Fort Moultrie. The changes in the inlet area were mainly confined within the jetties except at the Dynamite Hole area.

Figure 51 shows the maximum wave height field during the storm event for high SLC scenario. Figure 52 shows the spatial variation of current field at the peak wave height of the storm event for the high SLC scenario. The figure shows flow pattern during flood tide with current speed of about 0.77 m/second in the federal navigation channel near the harbor entrance. Figure 53 shows the morphology change at the end of the storm event for high SLC scenario. Changes in morphology in front of Morris Island are mainly observed in front of the Island spit. For Sullivan's Island,

morphology change mainly occurred in the area between the navigation channel and Fort Moultrie. The changes in the inlet area were mainly confined within the jetties and at the Dynamite Hole area.

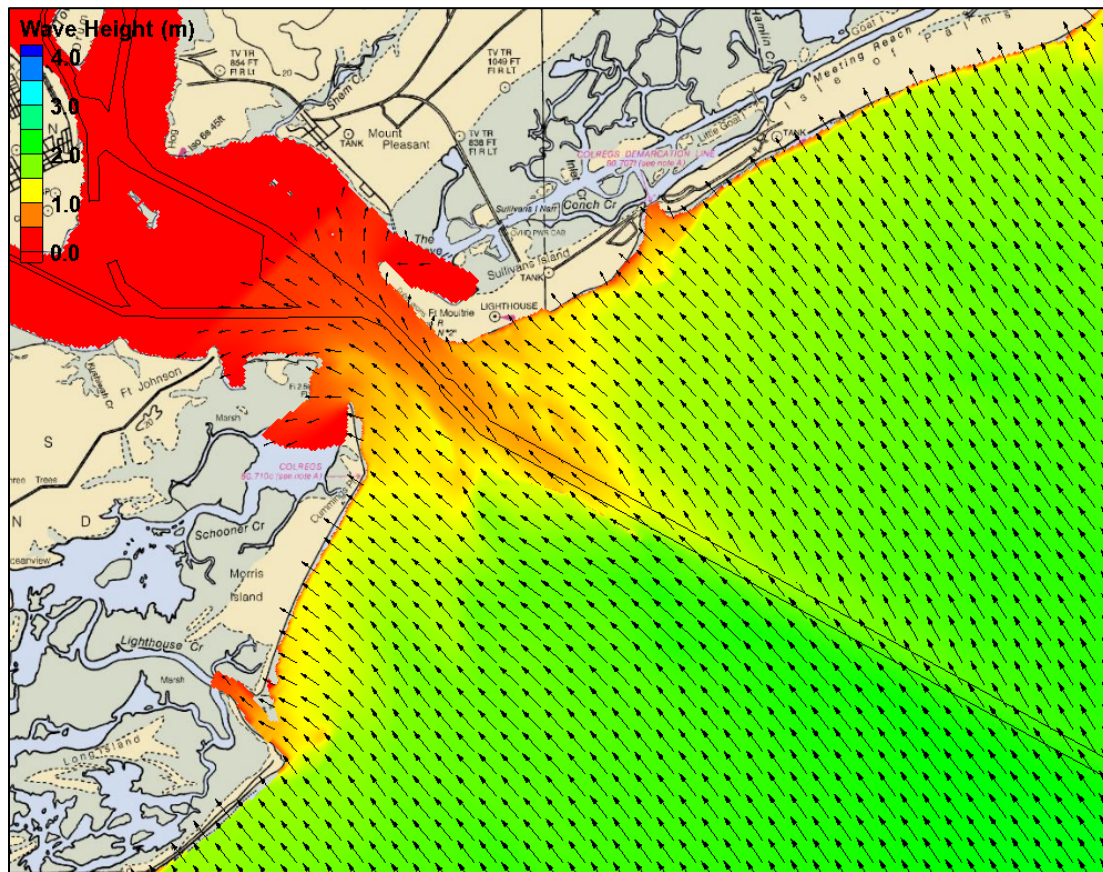


Figure 48- FWP maximum wave height field during the active winter month for high SLC scenario

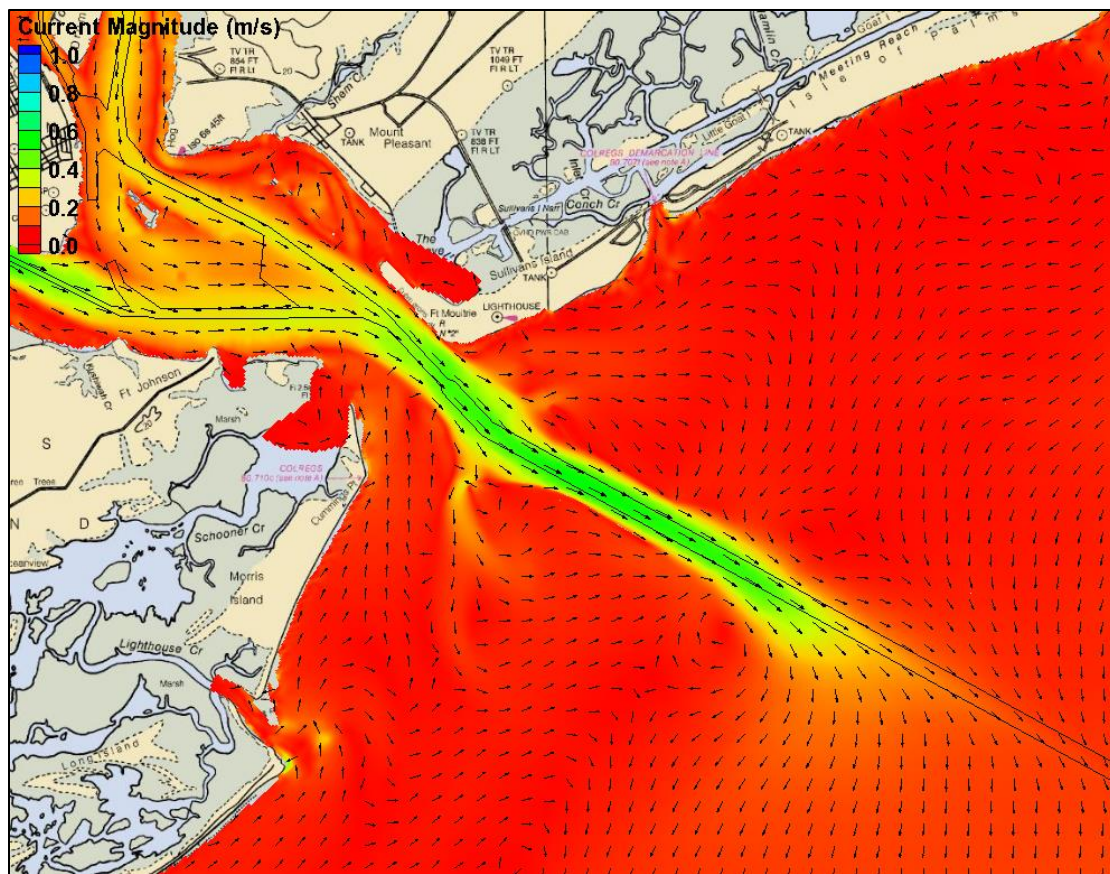


Figure 49- FWP flow pattern during the active winter month for high SLC scenario

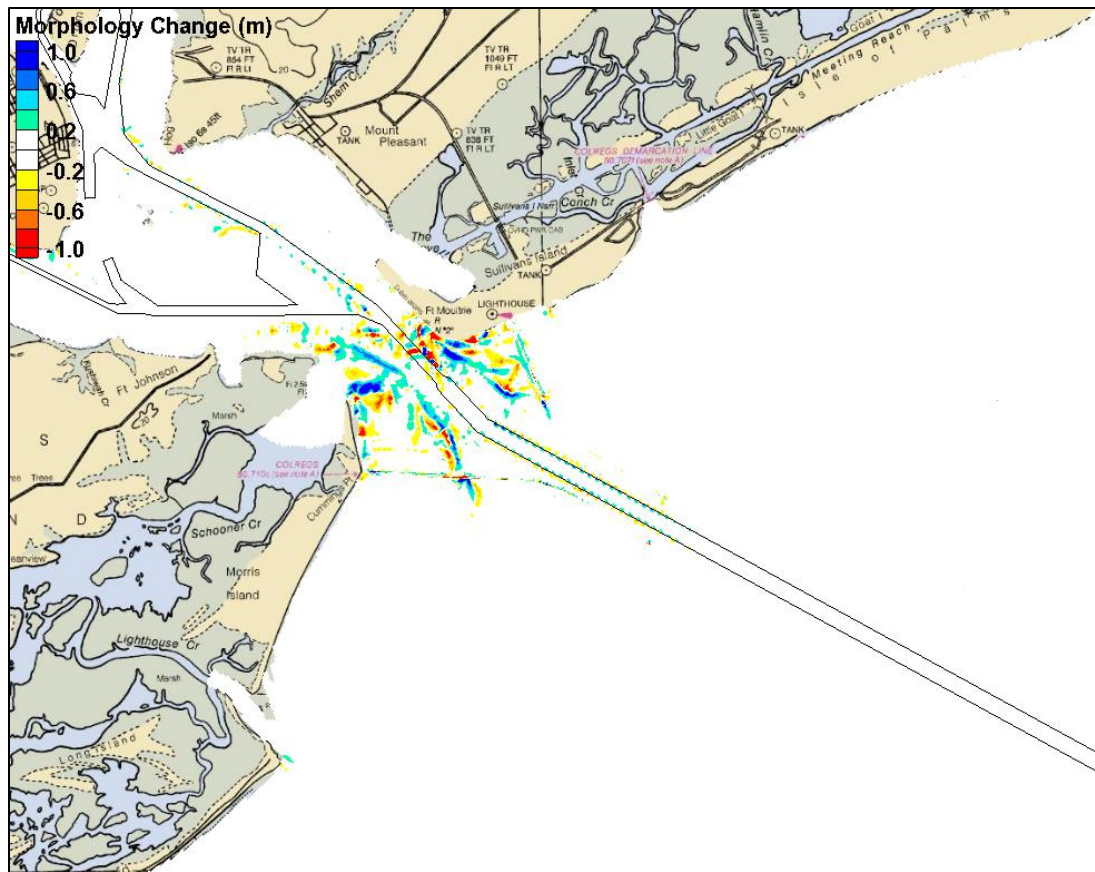


Figure 50- FWP modeled morphology change at the end of the active winter month for high SLC scenario

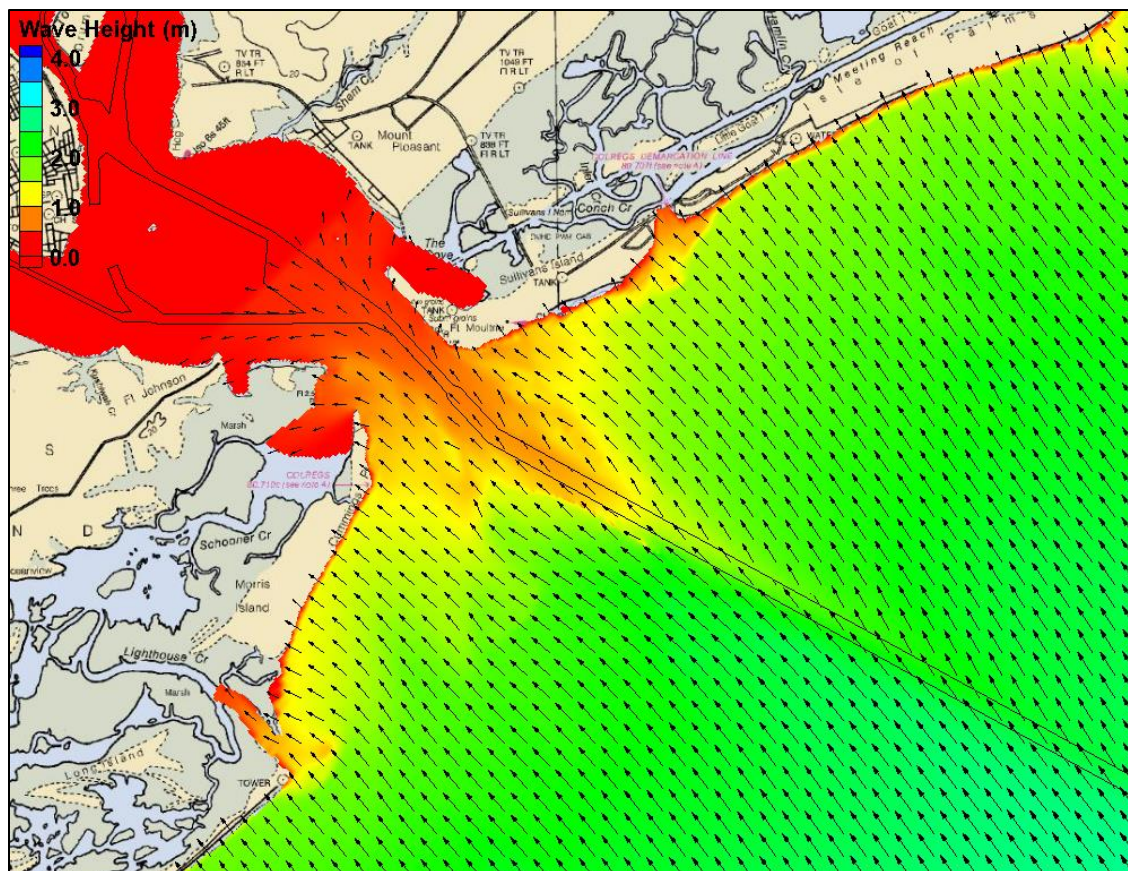
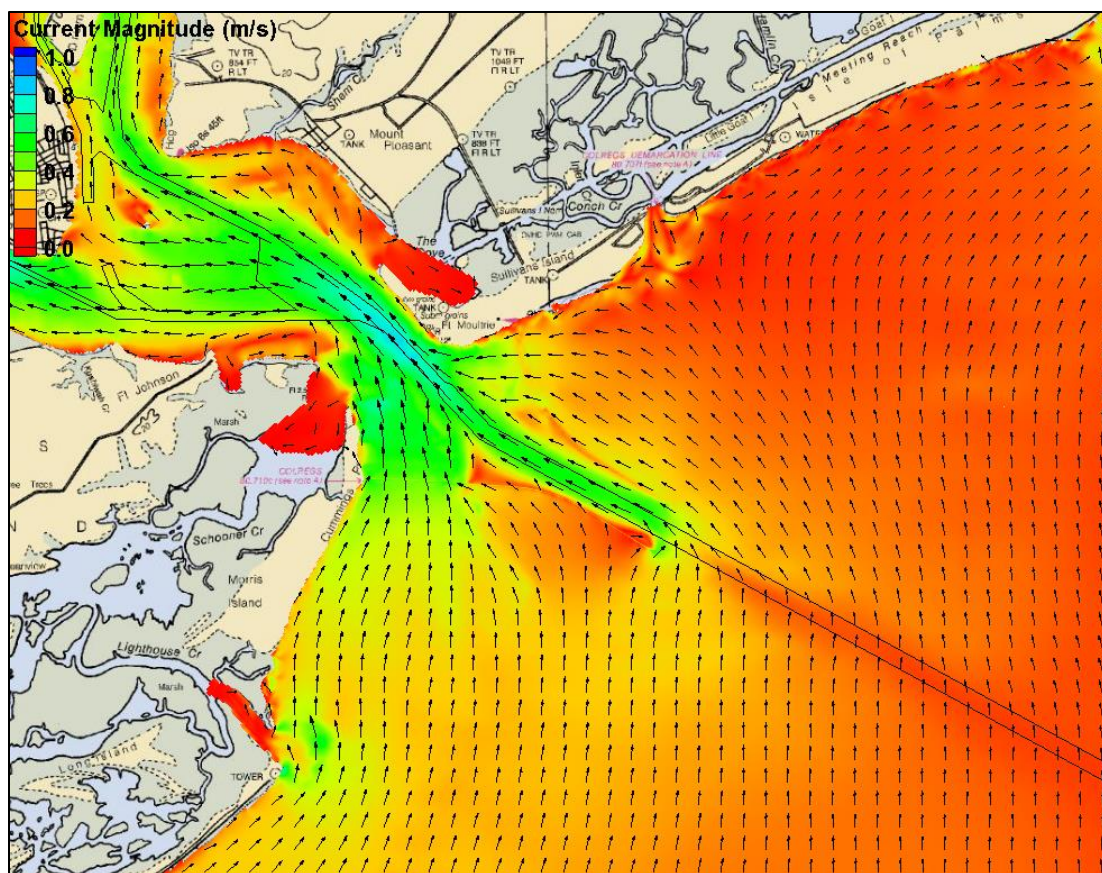
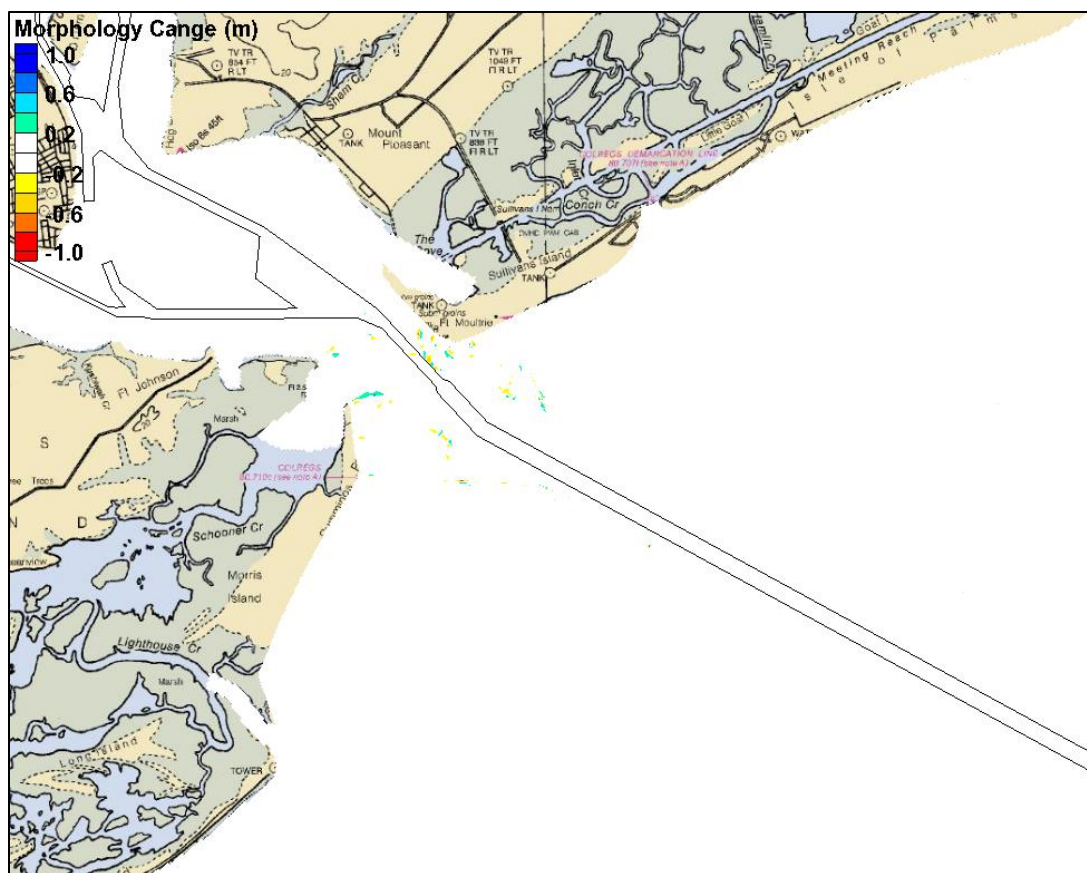


Figure 51- FWP maximum wave height field during the extreme storm event for high SLC scenario





8. EVALUATION OF THE DEEPENING PROJECT IMPACTS

The USACE is required to consider the option of “No Action” as one of the alternatives in order to comply with ER 1105-2-100 – Planning Guidance Notebook and the requirements of NEPA. With the future without-project, it is assumed that no project would be implemented by the Federal Government or by local interests to achieve the planning objectives. The future without-project forms the basis against which all other alternative plans are measured (USACE, 2015).

The differences between the with and without project conditions is performed to evaluate the potential effects on hydrodynamics and sediment transport that would be expected to occur in the future as a result of the project compared to the conditions that would occur in the future without the project (USACE, 2010).

8.1 Hydrodynamic Impact

The wave height difference was estimated by subtracting the FWOP wave height values from the FWP wave height values during the peak wave height of the simulation periods. The positive

wave height difference indicates wave height increase and the negative wave height difference indicates wave height decrease due to the project. Figure 54 shows the change in wave height field between FWP and FWOP during the active winter month for the three SLC scenarios. It can be seen from the figure that maximum change of about 7 cm was observed in the eastern vicinity of the channel while some higher values were observed at few cells along the southern jetty. Limited minimal wave height change occurred along the shorelines. The figure also shows that the pattern of wave height change is similar for the low, intermediate and high SLC scenarios but with different magnitude extent.

The change in water level due to the deepening project was evaluated by subtracting the FWOP water level values from the FWP values. Change of water levels between FWP and FWOP showed little difference (less than 1 cm) due to the deepening project for the three SLC scenarios.

Change in current magnitude was estimated by subtracting the FWOP current magnitude values from the FWP values during the peak wave height of the simulation periods. The positive values indicates current speed increase and the negative values indicates current speed decrease due to the project. Figure 55 shows the change in simulated current speeds between FWOP and FWP conditions, during the active winter month, for the three SLC scenarios. The figure shows that the deepening project resulted in mostly current magnitude decrease in the area confined within the jetties and at the Dynamite Hole area.

Figure 56 shows the change in wave height field, between FWP and FWOP, at the peak wave height of the extreme storm event for the three SLC scenarios. It can be seen from the figure that maximum change of about 6 cm was observed in the eastern vicinity of the channel while limited minimal wave height change occurred along the shorelines. The figure also shows that the pattern of wave height change is similar for the low, intermediate and high SLC scenarios but with different magnitude extent.

Change of water levels between FWP and FWOP showed little difference (less than 1 cm) due to the deepening project for the three SLC scenarios.

Figure 57 shows the change in simulated current speeds between FWOP and FWP conditions, at the extreme storm event, for the three SLC scenarios. The figure shows that the deepening project resulted in mostly current decrease in the channel area.

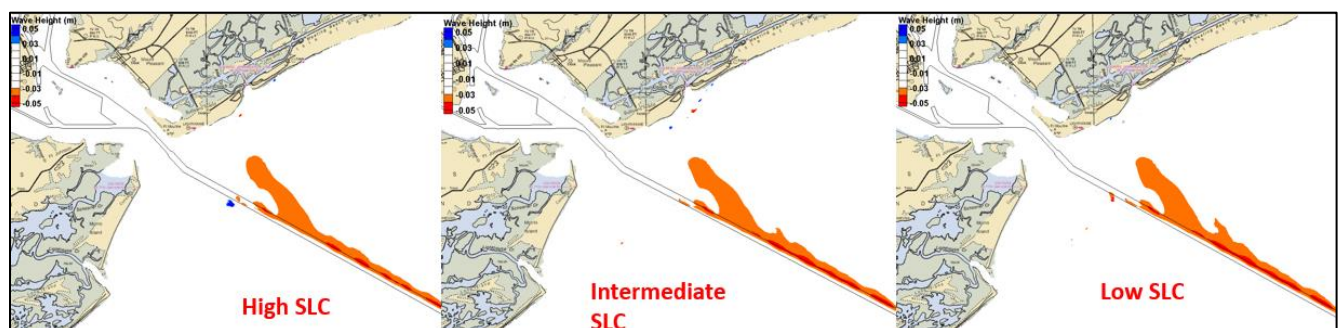


Figure 54- Change in maximum wave height field, between FWP and FWOP, during the active winter month

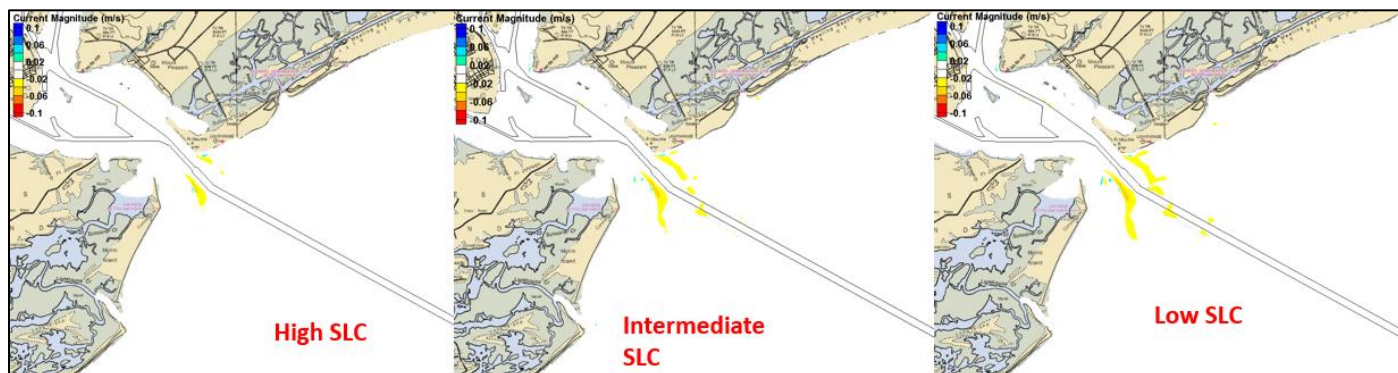


Figure 55- Change in current magnitude, between FWP and FWOP, during the active winter month

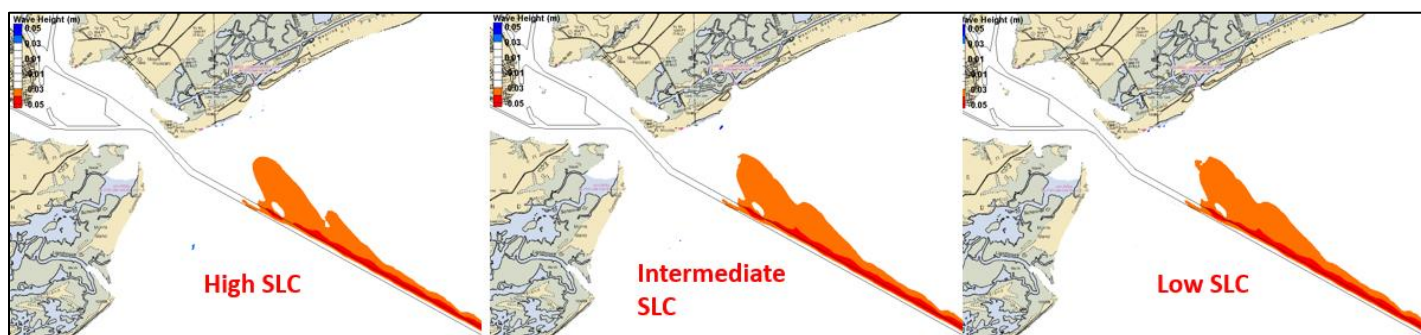


Figure 56- Change in maximum wave height field, between FWP and FWOP, during the extreme storm event

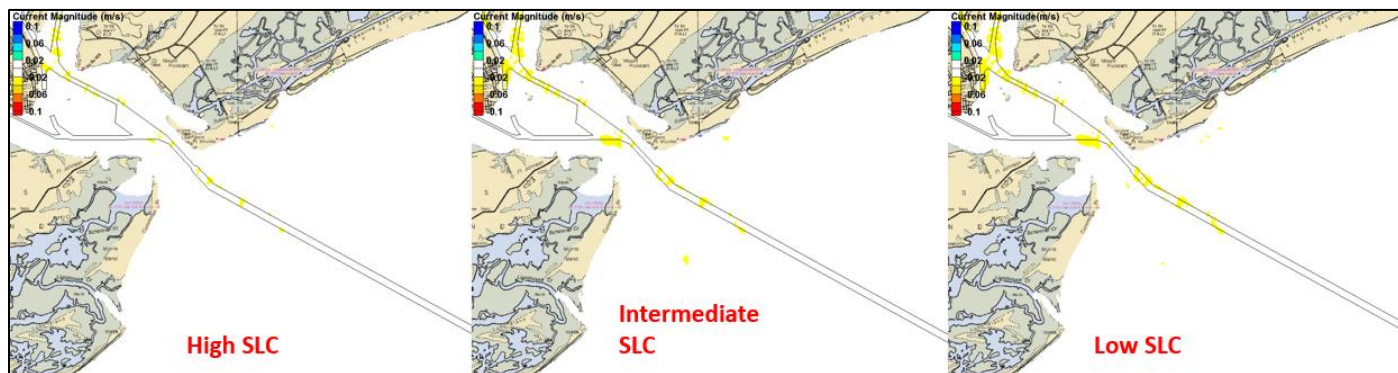


Figure 57- Change in current magnitude, between FWP and FWOP, during the extreme storm event

8.2 Morphology Impact

CMS flow and wave models were used to estimate morphology change for the future with and without scenarios. Modeled morphology change was calculated at the end of the simulation periods for future with and future without grid configurations during the long and short simulation periods.

Figure 58 shows the morphology change in the Charleston Harbor area at the end of the active winter month simulation period between the FWOP and FWP conditions for the three SLC scenarios. Change in morphology due to the deepening project was mainly observed in the navigation channel area.

Figure 59 shows the change in morphology between FWOP and FWP conditions, during the extreme storm event, for the three SLC scenarios. Change in morphology due to the deepening project were minimal.

Figure 60 shows the change in morphology, between FWP and FWOP, at transects along Morris and Sullivan's Islands shorelines during the active winter month. Minimal change in morphology is observed along Morris and Sullivan's Islands shorelines with maximum change of less than 4 cm and 8 cm in front of Cumming Pt of Morris Island and Fort Moultrie of Sullivan's Island respectively.

Figure 61 shows the change in morphology, between FWP and FWOP, at transects along Morris and Sullivan's Islands shorelines during the extreme storm event. Minimal change in morphology is observed along Morris and Sullivan's Islands shorelines with maximum change of less than 2 cm along in front of Fort Moultrie of Sullivan's Island.

In general, minor changes in morphology change was observed along Morris and Sullivan's Islands shorelines. Some morphology change is observed within the deepened channel.

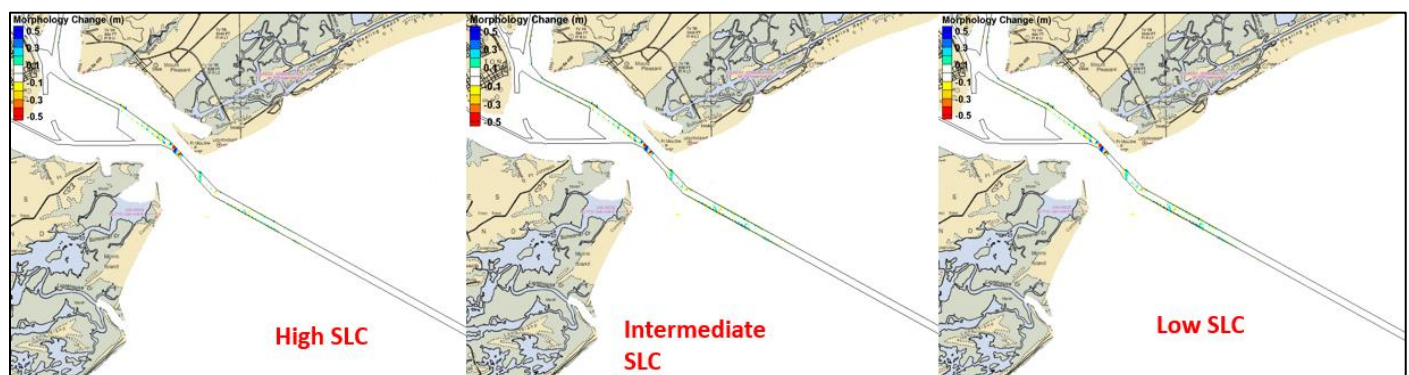


Figure 58 - Change in morphology, between FWP and FWOP, during the active winter month

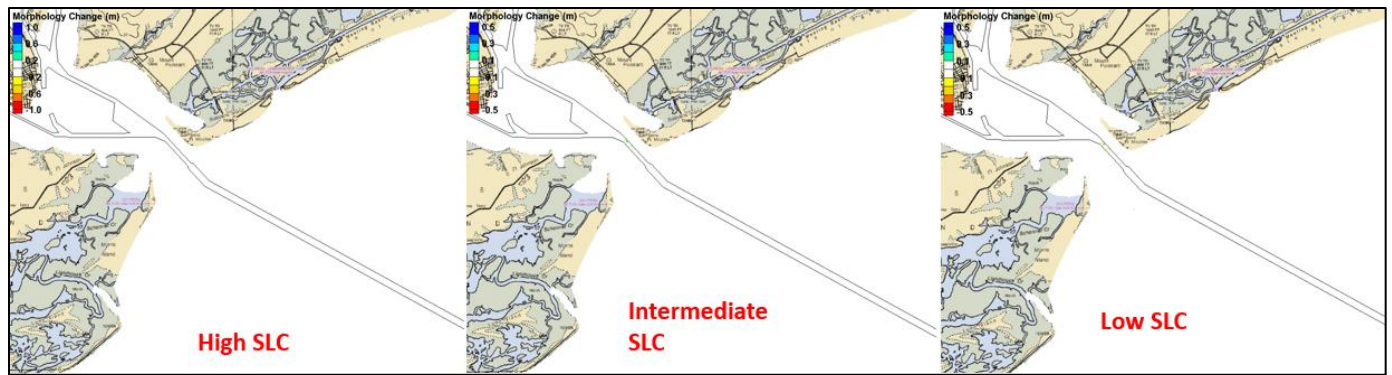


Figure 59- Change in morphology, between FWP and FWOP, during the extreme storm event

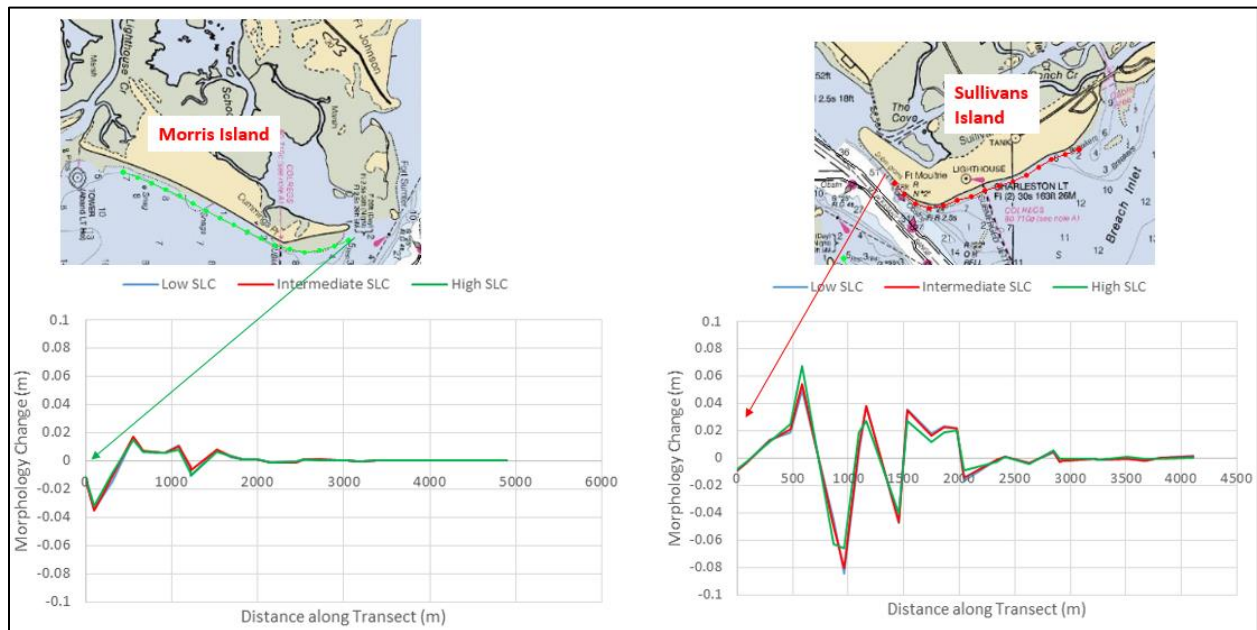


Figure 60- Change in morphology along Morris and Sullivan's Islands shorelines, between FWP and FWOP, during the active winter month

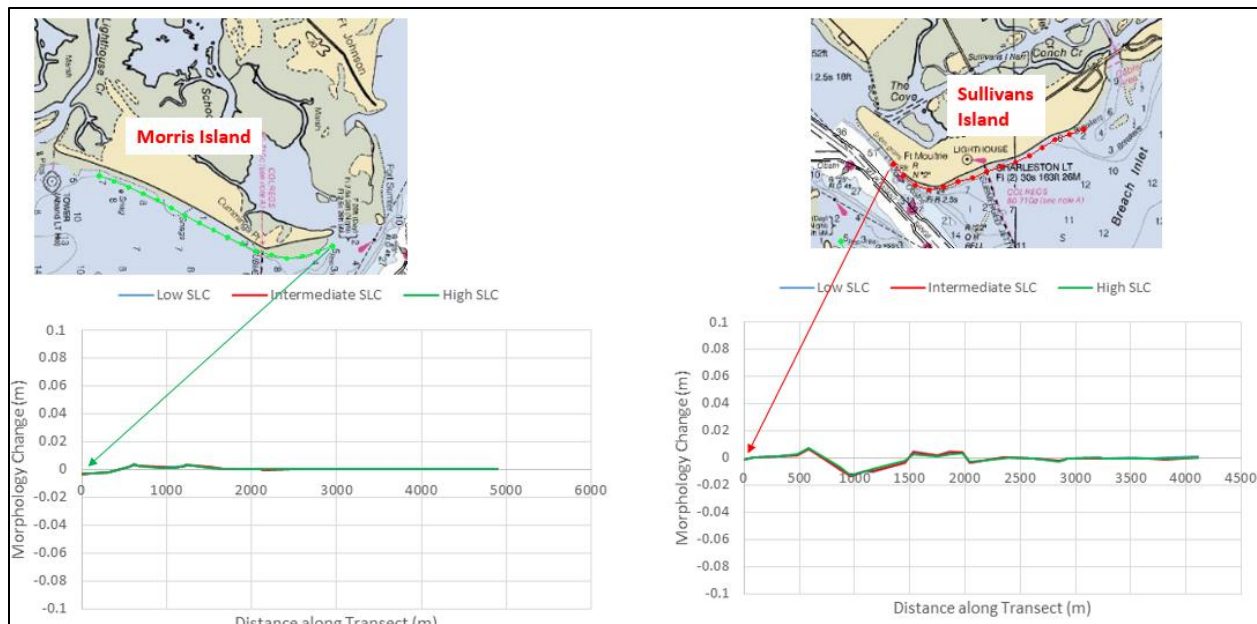


Figure 61- Change in maximum wave height along Morris and Sullivan's Islands shorelines, between FWP and FWOP, during the extreme storm event

9. CONCLUSIONS

SAC has initiated a study of deepening the existing Federal navigation system of Charleston Harbor. Additional channel depth would allow current and future shippers to more fully utilize larger class vessels and would reduce anticipated future congestion. The inner harbor channels leading to the Wando Welch container facility and the new Navy Base Terminal will be deepened from the existing -45 feet MLLW to -52 feet MLLW, and the channel from the new Navy Base Terminal to the North Charleston container facility from -45 feet MLLW to -48 feet MLLW. The entrance channel would be deepened from -47 feet MLLW to -54 feet MLLW.

This study includes numerical modeling of coastal hydrodynamics, wave transformation and sedimentation in the coastal area of Charleston Harbor. The numerical modeling is used to evaluate hydrodynamic and morphology change associated with the deepening project and address any adverse impact associated with the project.

The CMS flow and wave models were recalibrated because the original grids were modified. The performance of the CMS sediment model was assessed based on comparison of modeled and measured surveys of the Entrance Channel extending from June 25 to December 3 of 2013. The Entrance channel was not dredged during that period.

The calibrated CMS models were used to determine effects to the local wave, current and morphology conditions caused by the proposed channel deepening. Hydrodynamic and morphology change in the Charleston Harbor area, due to the deepening project, were estimated for one month of active winter weather and an extreme storm event.

Wave, current and morphology change were investigated during the selected simulation periods. The simulations included three scenarios that were used to assess how deepening the Charleston Harbor Channel would affect hydrodynamics and morphology in the vicinity of the Charleston Harbor. Base, Future With Project and Future Without Project conditions were investigated in this study. The base conditions are an estimate of possible conditions that may exist at the approximate time that the project is completed. FWP and FWOP conditions represent future states beginning in project year one and extending over a 50-year period of analysis. For the purposes of this study, the years 2022 through 2071 were examined.

The maximum wave height was 3.56 m and occurred at 19:00 on 26 December 2012 for the active winter month. During the extreme storm event, the maximum wave height was 4.34 m and occurred at 10:00 on 7 June 2013. Wave and current change was investigated during the peak wave conditions for the active winter month and the extreme storm event for the base, FWP and FWOP conditions for the high SLC scenario.

For the base scenario, maximum current speed of about 0.62 m/second was observed in the federal navigation channel between the jetties during the active winter month. Changes in morphology in front of Morris Island are observed in front of Cumming Pt and in front of the Island spit. Also, some change in morphology occurred in front of Fort Sumter. For Sullivan Island, morphology change mainly occurred in front of Fort Moultrie. The changes in the inlet area were mainly confined within the jetties and at the Dynamite Hole area. Maximum current speed of about 0.85 m/second was observed in the federal navigation channel near the harbor entrance during the extreme storm event. Changes in morphology in front of Morris Island are mainly observed in front of the Island spit. For Sullivan's Island, morphology change mainly occurred in the area between the navigation channel and Fort Moultrie. The changes in the inlet area were mainly confined within the jetties and at the Dynamite Hole area.

For the FWOP scenario, maximum current speed of about 0.52 m/second was observed in the federal navigation channel between the jetties during the active winter month. Changes in morphology in front of Morris Island are observed in front of Cumming Pt and in front of the Island spit. Also, some change in morphology occurred in front of Fort Sumter. For Sullivan's Island, morphology change mainly occurred in front of Fort Moultrie. The changes in the inlet area were mainly confined within the jetties except at the Dynamite Hole area. Maximum current speed of about 0.78 m/second was observed in the federal navigation channel near the harbor entrance during the extreme storm event. Changes in morphology in front of Morris Island are mainly observed in front of the Island spit. For Sullivan's Island, morphology change mainly occurred in the area between the navigation channel and Fort Moultrie. The changes in the inlet area were mainly confined within the jetties and at the Dynamite Hole area.

For the FWP scenario, maximum current speed of about 0.51 m/second was observed in the federal navigation channel between the jetties during the active winter month. Changes in morphology in front of Morris Island are observed in front of Cumming Pt and in front of the Island spit. Also, some change in morphology occurred in front of Fort Sumter. For Sullivan's Island, morphology change mainly occurred in front of Fort Moultrie. The changes in the inlet area were mainly confined within the jetties except at the Dynamite Hole area. Maximum current speed of about 0.77 m/second was observed in the federal navigation channel near the harbor

entrance during the extreme storm event. Changes in morphology in front of Morris Island are mainly observed in front of the Island spit. For Sullivan's Island, morphology change mainly occurred in the area between the navigation channel and Fort Moultrie. The changes in the inlet area were mainly confined within the jetties and at the Dynamite Hole area.

The change in hydrodynamics due to increasing the project depth was examined for the with and without project during Year 50. The model predicted that increasing the project depth will have minimal change in water level of less than 1 cm. In general, changes in wave height between the future with and the future without condition were less than 7 cm and were mainly observed in the eastern vicinity of the channel. Some higher values of wave change were observed at few cells along the southern jetty during the long simulation period. Limited minimal wave height change occurred along the shorelines. The deepening project resulted in mostly current magnitude decrease in the area confined within the jetties and at the Dynamite Hole area at the peak wave height for the active winter month. During the peak wave height for the extreme storm event, the deepening project resulted in mostly current decrease in the channel area.

CMS flow and wave models were used to estimate morphology change for the future with and without scenarios. Change in morphology due to the deepening project was mainly observed in the navigation channel area at the end of the active winter month simulation period. Change in morphology due to the deepening project were minimal during the extreme storm event.

During the active winter month, minimal change in morphology was observed along Morris and Sullivan's Islands shorelines with maximum change of less than 4 cm and 8 cm in front of Cumming Pt of Morris Island and Fort Moultrie of Sullivan's Island respectively. During the extreme storm event, minimal change in morphology was observed along Morris and Sullivan's Islands shorelines with maximum change of less than 2 cm in front of Fort Moultrie of Sullivan's Island.

In general, the pattern of morphology change at the end of the simulation periods was similar for the Base, Future With Project and Future Without Project conditions. Increasing the project depth was predicted to have very little effect on the wave height field, water level elevations and current flow in the vicinity of Charleston Harbor. Change in morphology due to the deepening project was mainly observed in the navigation channel area and minimal changes were observed along portions of Morris and Sullivan's Islands shorelines adjacent to the inlet and accordingly no change in morphology occurred in front of Folly Island.

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